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Energy and exergy analyses of various typical solar energy applications: A comprehensive review

Sunil Kumar Sansaniwal*, Vashimant Sharma, Jyotirmay Mathur

Centre for Energy and Environment, Malaviya National Institute of Technology, Jaipur 302017, Rajasthan, India

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ABSTRACT

The overuse of fossil fuels in real life applications has caused their rapid depletion and fast climate change due to global warming and thus access to eco-friendly energy resources has become essential to meet the growing demand of clean energy. With this view, solar energy has proven to be an effective alternative and clean source of energy for the sustainable development of the society worldwide. Solar energy is a cheap, abundant and everlasting source of renewable energy and thus it can be integrated with different systems deals with energy consumption to overcome the dependency of present society on conventional fuels. Such integration of solar energy has given an opportunity for several studies based on the energy and exergy approaches. The energy analysis is very crucial in the study of process effectiveness while the exergetic analysis is another important tool to investigate the realistic behaviour of process involving various energy losses and internal irreversibility. The main objective of this article is to bring out valuable recommendations for wide exploitation of solar energy systems for different applications, from a thermodynamics perspective. Therefore, the present article has summarized the previous findings on energy and exergy analyses of different solar energy systems (solar drying, solar air conditioning and refrigeration, solar water heating, solar cooking and solar power generation through solar photovoltaic and concentrated solar power techniques used for various heat and power generation applications).

1. Introduction

Today, the replacement of fossil fuels with renewable one has become an urgent need for the clean and sustainable development of energy sector, globally. In renewable energy resources, solar energy is the promising alternative to meet the increasing demand for clean energy. It is clean, cheap and abundantly available around the year and thus attracts many researchers for its use in various theoretical and experimental studies. Integration of solar energy with various types of other energy systems plays an important role in the reinforcement of sustainable development of technology. For example, both heat and electricity can be obtained from the integration of solar thermal components with solar photovoltaic (PV) cells to form a hybrid unit. However, cost-effective design of these cells is the keen interest among the researchers in this area. Besides, these energy systems are also suffering from various bottlenecks (low conversion efficiency, high initial investment cost, long payback period and unavailability of skilled manpower). Therefore, hybrid energy systems in our real-life applications requires special attention for their fast and sustainable developments [1,2]. The working performance of these systems can be investigated based on the energy and exergy approaches. The former is obtained from the first law of thermodynamics, accounting the quantity of energy in the entire system. While the latter is based on the second law of thermodynamics which involves irreversibility and represents quality of energy in system. The exergy based analysis is very important to identify the cause, location and magnitude of various irreversibilities claiming reduction in overall efficiency of system.

Thus, the finding of root cause of irreversibilities can be helpful in the optimum designing and effective utilization of energy in various applications. Moreover, the exergy analysis also provides true sense of diversion of existing system from the ideal one [3]. The solar energy can be utilized (directly or indirectly) in different applications such as solar drying, solar refrigeration and air conditioning, solar water heating, solar cooking and solar power generation. The drying of various commodities (fruits, vegetables, herbal medicines and agricultural products) is very important for their future uses through preservation. However, drying of food products is an energy intensive which consumes 7–15% of industrial energy in most of the countries (like United States, Germany, Denmark, Canada, United Kingdom and France). Further, around 35% of energy consumed in drying is used in

* Corresponding author.
E-mail address: sansaniwal@gmail.com (S.K. Sansaniwal).

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Nomenclature

A_c	area of collector (m^2)
C	specific heat (kJ/kg K)
$\dot{E}$	energy flow rate (kW)
$\dot{E}x$	exergy flow rate (kW)
$\dot{F}$	exergy rate of fuel (kW)
h	specific enthalpy (kJ/kg)
I	current (Amps)
I_s	intensity of solar radiation (W/m^2)
$\dot{I}$	rate of irreversibility (kW)
L	latent heat of vaporization (J/kg)
M	moisture content
$\dot{m}$	mass flow rate (kg/s)
$\dot{P}$	exergy rate of the product (kW)
P_f	energy input to the fan (kWh)
P	pressure (N/m^2)
$\dot{Q}$	heat transfer rate (kW)
R	ideal gas constant (kJ/kg K)
$\dot{S}_{mass}$	entropy rate at mass rate (kW/K)
$\dot{S}_{heat}$	entropy rate at heat rate (kW/K)
s	specific entropy (kJ/kg K)
t	time period (s)
ΔT	temperature difference
T	temperature (°C or K)
U_L	overall heat loss coefficient (W/m^2K)
V	voltage (V)
$\dot{W}$	work rate (kW)
W	weight of water evaporated from product

Subscripts

a	air, ambient
abs	absorber
aex	annual exergy output
as	absolute humidity of air (%)
b	body
c	collector
cv	control volume
cond	condenser
d	destruction, drying
da	drying air
e	cooling load
el	electricity
eva	evaporator
fin	final state
out	outlet
gen	generator, generation
ini, in	initial state, inlet
i	number of elements
l	losses
m	maximum power point, mass, mean
o	overall, output
oc	open circuit
pv	photovoltaic
p	pump
r	roof
s	surface, solar radiation
sr	south roof
s,h	solar heat input
sc	short circuit, solar cell, solar cooker
th	thermal, theoretical
U	useful thermal energy
w	water
0	dead (reference state)
∞	ambient

Greek symbols

ε	exergy or second law efficiency
η	energy or first law efficiency
Ψ	flow exergy (kJ/kg)
δ	fuel depletion rate
Δ	interval
χ	relative irreversibility
ξ	productivity lack
β	packing factor of solar cell
ρ	density (kg/m3)
f	exergetic factor, product

pulp and paper industry and only 5% of it is being utilized for chemicals. Thus, higher cost associated with drying is key challenge and directs researchers to look for the alternative source of energy, solar energy in indirect form in particular [4,5]. In solar air heating, ambient air heats up directly by solar energy and then used as heating medium for space heating, air heating and drying applications. In recent years, various types of collectors have been developed for drying purposes [6]. Besides, the auxiliary source of heating (like electric heaters, phase change materials, desiccants, water and gravels) are also in trend for continuous operation during adverse climate conditions.

However, optimum designing leading to energetic and exergetic performance enhancements of solar drying can only be obtained through mathematical modelling and simulation techniques [7–19]. The solar refrigeration and air conditioning is another emerging application capable of achieving the thoughtful cooling or fair air conditioning in hybrid HVAC systems. Solar energy as peak load bearer is the recent practice in energy efficient refrigeration and air conditioning systems. However, working performance of these systems can only be improved through energy and exergy approaches. Solar water heating is an attractive and common practice to meet the heat requirements of hot water applications in domestic and industrial establishments. Various collectors such as flat plate collector (FPC),

Table 1
Solar energy collectors [27].

Tracking	Collector type	Absorber type	Concentration ratio	Operating temperature (°C)
Stationary	Flat plate collector (FPC)	Flat	1	30–80
	Evacuated tube collector (ETC)	Flat	1	50–200
	Compound parabolic collector (CPC)	Tubular	1–5	60–240
Single axis	Linear Fresnel reflector (LFR)	Tubular	10–40	60–250
	Parabolic trough collector (PTC)	Tubular	15–45	60–300
	Cylindrical trough collector (CTC)	Tubular	10–50	60–300
Two axes	Parabolic dish reflector (PDR)	Point	100–1000	100–500
	Heliostat field collector (HFC)	Point	100–1500	150–2000

evacuated tube collector (ETC) and compound parabolic collector (CPC) are extensively used in water heating applications. However, the performance of each collector unit can be evaluated based on energy and exergy criteria, separately, as covered under solar water heating section in this article. The implementation of fins in solar water heating leads to enhance the heat transfer conditions through different modes (conduction, convection and radiation) [20]. Various researchers have introduced several unique features in collector units to improve their heat absorbing characteristics [21–26]. Various kinds of solar energy collectors are listed in Table 1.

Cooking is the most important activity for people around the globe but it is energy intensive. Solar cooking is a promising technique which not only saves fuel but also keeps the environment eco-friendly through reducing the health hazards and deforestation. However, due to intermittent nature of solar energy, cooking can only be performed during day time. So, these systems can be further integrated with other supplementary heat sources (biomass heating, resistance heating and phase change materials) for cooking practices during adverse climate conditions and cooking at night hours. Besides, solar cooking may also be helpful to bring prosperity in rural living standards where most of the population is not able to access the commercial fuels like LPG and electricity [28]. The power generation from solar energy has also received much attention worldwide due to unstable and exhaustive market of conventional fuels. It is comprised of mainly two major elements namely, solar photovoltaic (PV) and concentrated solar power (CSP) techniques for heat and power generation applications. In PV, solar energy can be used directly by photosynthesis and get converted into electricity. In present market, three types of solar PV modules (viz. mono-crystalline silicon, multi-crystalline silicon and ribbon silicon-based modules) are widely used at large scale.

The efficiency of monocrystalline silicon-based modules is more than that of multi-crystalline silicon, however, the former is more expensive. The conversion efficiency of multi-crystalline silicon is observed to vary from 12% to 15% and can be enhanced up to 20% through improved cell designs [29,30]. On the other hand, CSP technologies (LFR, PTC, CTC, PDR and HFC) are popular and rapidly developed, especially for heat and power generation applications. However, they are capital intensive and have poor performance at small scale [31]. Therefore, several opportunities can be explored to augment the research and development of these systems for wide exploitation of solar energy. In the present article, a comprehensive review on energy and exergy analyses of various solar energy systems (i.e. solar drying, solar refrigeration and air conditioning, solar water heating, solar cooking and solar power generation through solar photovoltaic and concentrated solar power techniques) used for various heat and power generation applications have been presented with valuable recommendations from thermodynamics perspectives.

2. Energy and exergy analysis

In general, energy is a property of an object which enables it to perform work through transformation into different forms. Energy analysis can be carried out using basic laws of thermodynamics, to study the work performance of process. Energy is manifested in mainly two forms viz. macroscopic and microscopic. The macroscopic forms (kinetic and potential energies) are accounted with respect to reference frame and are influenced by many external effects (gravity, electricity, surface tension and magnetism). While the microscopic forms (like internal energy) are related to the molecular characteristics of the system and are independent of external reference frames. Such energies depend on the inherent properties of material like composition and physical form together with environmental effects (temperature, pressure and electric field). Therefore, absolute value of energy associated with system is difficult to measure, however; change of energy is the sole interest in energy analysis of various solar systems [3,32–34]. The first law of thermodynamics deals only with the quantity of energy and asserts energy change of system accompanied by energy change of surrounding. However, quality of energy is more important to identify work potential of system and is expressed by term 'exergy'. When exergy losses its quality in a process, it gets destroyed and thus affects the overall work performance. Therefore, energy is conserved while exergy is accumulated.

As compared to low exergy content of energy, high exergy content is more important to obtain desirable performance of the system [3]. Exergy calculation is based on the second law of thermodynamics which deals with quantity and quality of energy relative to the reference state. Energy and exergy efficiencies are also known as first and second law efficiency, respectively. In general, exergy efficiency is often calculated to be lower than that of energy efficiency due to the involvement of irreversibilities caused by thermodynamics imperfections during the process [35,36]. Many kinds of exergy are observed due to the presence of various random activities such as macroscopic forms of energy, turbulence flow of molecules and the concentration of species with respect to dead state [37]. The work potential of a real system can only be estimated by defining a state corresponding to zero-work potential because the equilibrium condition is technically correct for reference state. In exergy analysis, both mass and energy conservation principles may be applied together for design and analysis of different solar energy systems. The ideality, location, type and magnitude of various losses occurred in process can be identified and rectified accordingly. Therefore, the optimum design, resource utilization, sustainability and impact of environment on energy may be investigated through exergetic analysis. Moreover, exergy analysis is helpful in assessing and comparing the various processes and systems meaningfully and rationally [3,32].

2.1. General relations

In a steady flow process, work and heat interactions, rate of exergy decrease, rate of irreversibility, energy and exergy efficiencies can be obtained by using four balance equations (i.e. mass, energy, entropy and exergy) as given below [35,38–40]:

2.1.1. Mass, energy, entropy and exergy balances

The general mass balance equation in rate form may be expressed as follows:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

Similarly, the general energy balance equation may be expressed in rate form given as:

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \tag{2}$$

The general entropy balance equation in rate form can be expressed as follows:

$$\dot{S}_{in} - \dot{S}_{out} + \dot{S}_{gen} = 0 \tag{3}$$

Considering positive heat transfer to system, Eq. (3) may be rearranged given as:

$$\dot{S}_{gen} = \sum \dot{m}_{out} s_{out} - \sum \dot{m}_{in} s_{in} - \sum \frac{\dot{Q}_K}{T_K} \left(\because \dot{S}_{mass} = \dot{m} \text{and} \dot{S}_{heat} = \frac{\dot{Q}_K}{T_K} \right) \tag{4}$$

Further, exergy destruction or irreversibility rate ($\dot{I}$) can be evaluated as follows [41]:

$$\dot{I} = \dot{E}x_{dest} = T_0 \dot{S}_{gen} \tag{5}$$

The general exergy balance in rate form may be written given as:

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{dest} \tag{6}$$

Further, Eq. (6) can be elaborated as follows:

$$\dot{E}x_{dest} = \dot{E}x_{heat} - \dot{E}x_{work} + \dot{E}x_{mass,in} - \dot{E}x_{mass,out} \quad (7)$$

Where $\dot{E}x_{heat} = \sum\left(1 - \frac{T_0}{T_K}\right)\dot{Q}_K$, $\dot{Q}_K$ is heat transfer rate through boundary at temperature T_K with location K.

$\dot{E}x_{work} = \dot{W}$ (work rate)

$\dot{E}x_{mass,in} = \sum \dot{m}_{in}\psi_{in}$ And

$\dot{E}x_{mass,out} = \sum \dot{m}_{out}\psi_{out}$

Also, the specific or flow exergy (ψ) may be calculated as follows:

$$\psi = (h - h_0) - T_0(s - s_0) \quad (8)$$

Total exergy of system may be divided into four components (physical exergy, kinetic exergy, potential exergy and chemical exergy) provided negligible influence of various effects (electricity, magnetism, surface tension and nuclear reactions) on the system.

2.1.2. Energy and exergy efficiencies

The performance analysis of most of energy systems is based on energy analysis which accounts only energies at inlet and outlet of the system [3]. The energy based analyses of various systems have been carried out by many researchers over the past decades. Therefore, the terms energy and exergy efficiencies are very important to study the thermal performance of various systems. In this article, we have focused more on exergetic behaviour of various solar energy systems under different working conditions [40,42]. Two different approaches (brute force and functional) have been considered as prominent studies to define exergy efficiency. Former is defined as the ratio of resultant output exergy to resultant input exergy while the latter is defined as the ratio of exergy associated with desired energy output to exergy related to energy claiming the desired output. So, the brute force approach may be implemented irrespective of the nature of system while the functional approach requires a thorough study of the system [43]. Overall, the exergy efficiency may be defined as the ratio of total exergy output to total exergy input i.e.

$$\varepsilon = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} = 1 - \frac{\dot{E}x_d}{\dot{E}x_{in}} \quad (9)$$

2.1.3. Exergy improvement potential

Exergy improvement is an important criterion in optimum designing of solar systems and can be achieved through minimizing exergy losses or irreversibilities occurred in the process. Some studies on potential of exergy improvement are presented here. Ibrahim et al. [44] studied energy and exergy analyses along with exergetic improvement potential of a building integrated with PV/T comprised of a combined PV module and spiral flow absorber. The improvement potential of system was observed to increase with increase in solar radiation (Fig. 1) and was determined by using Eq. (10) [45]:

$$IP = (1-\varepsilon)\dot{E}x_d \quad (10)$$

Based on energy analysis, average PV, thermal and PV/T energy efficiencies were obtained to be 10.8%, 48.0% and 59.0%, respectively (for mass flow rate of 0.027 kg/s and solar radiation of 690 W/m^2). While PV/T exergy efficiency and improvement potential were reported to be 13.1% and 314 W, respectively. Kuzgunkaya and Hepbasli [46] experimentally studied the exergetic performance of a ground source heat pump (GSHP) dryer for drying laurel leaves (Laurus nobilis). The exergy efficiencies of GSHP and whole system were reported to be 21.1% and 15.5%, respectively. The energy based COP of GSHP and whole system were obtained to be 2.88 and 2.65 whereas for exergy based, it was 0.196 and 0.174, respectively. The maximum potential of exergetic improvement was calculated to be 551.63 W by using expression given by [47]. Recently, Fudholi et al. [47] also investigated energy and exergy analyses of a hybrid solar drying system (comprised of V-groove air collector, fans, rotating drying chamber, diesel burner and PV modules) for drying silver jewfish (Johnius saldodo). The collector and dryer efficiency were obtained to be 41.0% and 23.0%, respectively (for mass flow rate of 0.0778 kg/s and solar radiation of 540 W/m^2). Whereas the average exergy efficiency of drying system was calculated to be 31.0%. Further, the total energy consumption of drying process was estimated to be 89.9 kWh (Contribution of solar energy (66%), diesel burner (29%) and fan (5%)). The average exergetic improvement potential of 236 W was also calculated.

Gunerhan and Hepbasli [48] presented the performance evaluation and exergetic modelling of solar water heating for residential applications. The exergy efficiencies of solar collector and whole system were reported to vary from 2.02% to 3.37% and 3.27–4.39%, respectively. Highest exegetic improvement potential rate was observed in FPC followed by heat exchanger and circulating pump. The schematic view of solar water heating is shown in Fig. 2.

According to [45], maximum exergy potential rate and exergy improvements were observed in collector unit having maximum exergy destructions of 95% followed by heat exchanger (2.7%) and circulating pump (2.3%). Aman et al. [49] developed a thermodynamics model for solar cooling working based on NH_3-H_2O absorption for residential application. More irreversibility was observed in absorber (63%) followed by generator (13%) and condenser (11%). The value of COP of the system was obtained to be 1.86, however, this value was reported to decrease (up to 0.60) due to exergy degradation of all components of the system. The overall efficiency of cooling system was found lower as compared to LiBr-H_2O based cooling and thus latter was recommended to achieve the higher exergetic performance.

Joshi et al. [50] investigated the working performance of hybrid PV/T system in terms of energy and exergy efficiencies and improvement potential factors. The energy and exergy efficiencies of hybrid PV/T system were found to be 45.0% and 16.0%, respectively. The exergetic improvement potential of 250–610 W was also obtained corresponding to the exergy destructions. A high improvement potential was expected since only 11–16% of exergy from solar radiation was estimated to be utilized in the process. Overall, the working performance was observed in good agreement with experimental data available in the literature. The variations in overall exergy of system, exergy of solar radiation and improvement potential are illustrated in Fig. 3.

Therefore, exergy loss (exergy waste and exergy destruction) indicates possible improvement in overall performance of the system. However, the complete and instant recovery of such losses is not possible since every part of system is interconnected and thus their work performance depends on other parts as well. Hence, exergy improvements in one part may result in higher exergy losses in other

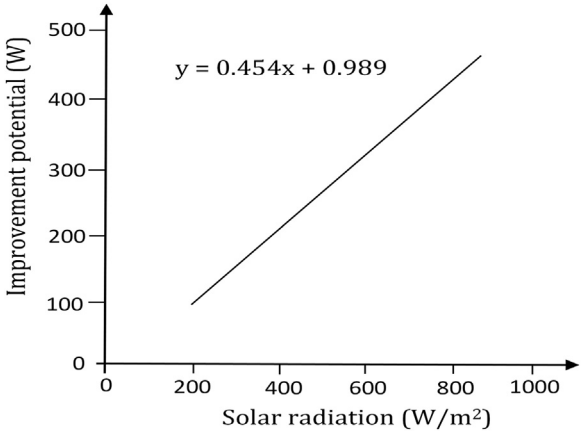

Fig. 1. Variations in improvement potential with solar radiation [44].

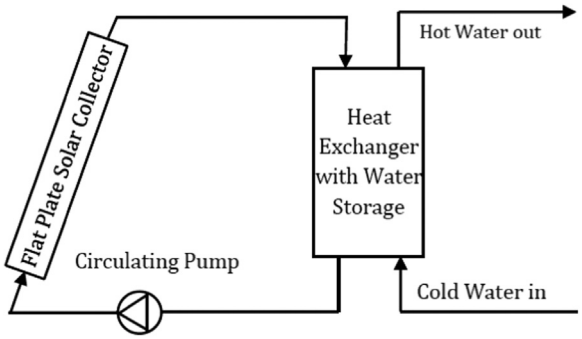

Fig. 2. Solar water heating [48].

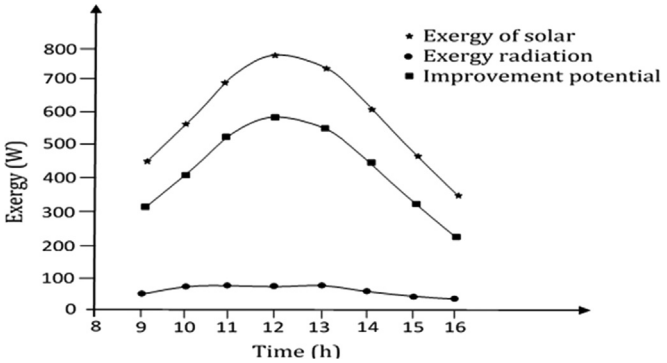

Fig. 3. Exergy of system, exergy of solar radiation and improvement potential w.r.t time [50].

parts. Such approach may also lead to higher total resultant losses than original process configuration. Therefore, more studies with real and rational approaches are required to investigate the exergetic improvement in various solar energy technologies.

2.1.4. Other thermodynamics functions

Several other thermodynamics parameters (fuel depletion ratio, relative irreversibility, productivity lack and exergetic factor) may also be considered in thermal analysis of different energy systems [51].

Fuel depletion ratio

$$\delta_i = \dot{I}_i/\dot{F}_T \tag{11}$$

Relative irreversibility

$$\chi_i = \dot{I}_i/\dot{I}_T \tag{12}$$

Productivity lack

$$\xi_i = \dot{I}_i/\dot{P}_T \tag{13}$$

Exergetic factor

$$f_i = \dot{F}_i/\dot{F}_T \tag{14}$$

3. Solar drying

Open sun drying (OSD) of various commodities (i.e. food, vegetables, herbs, crops and meat) is not a new practice and is as old as the human civilization. However, many external drying parameters (temperature, air flow rates, heat input and humidity) cannot be controlled in OSD and hence, it is attributed to larger drying period and undesirable drying quality. The quality of drying product is also affected due to various ungovernable facts (rain, hailstorm, heavy wind, debris, insects and stray animals) [52]. On the other hand, solar drying has been considered as an improved drying technique with high product quality, easiness, durability and economic viability. It also ensures high nutrition values of drying products and keeps the environment eco-friendly. In solar drying, several improvements (auxiliary heating, phase change materials, design augmentation of collector and drying chamber) are made to achieve the required temperature conditions for drying of products having different moisture levels [53–55].

Different types of solar dryers (direct, indirect and hybrid) have been developed so far and simulated for optimum drying conditions to enhance the overall performance of the system. The average drying efficiencies of direct solar dryers have been reported to vary from 20.0% to 40.0% for different products, climate conditions and air flow rates. However, drying quality may not be up to the market standards due to non-uniform heating of product. Whereas indirect solar dryers have been observed to be more effective due to their better control over drying parameters and good collector efficiency (18.0–40.0%) and drying efficiency (13.0–25.0%). Though the drying efficiency of indirect solar dryer is less than direct solar dryer but the quality of product obtained in former is far better than latter. The hybrid solar dryers have been identified to have the high collector efficiency (62.5%) and drying efficiency (17.0–29.0%) which can be improved through minimizing thermal losses and exergy destructions [6].

3.1. Energy analysis

Indirect solar dryer mainly consists of two components namely, FPC and drying chamber. The FPC comprises an absorber plate made of heat conducted materials (like copper, aluminium and mild steel), covered with glass plate and the whole drying unit is insulated to minimize the thermal losses. Forced convection heat transfer mode has been considered for uniform drying of product inside the drying chamber.

Mass of water removed from drying product may be calculated as follows [56]:

$$W = \frac{m_o(M_{in} - M_{fin})}{100 - M_{fin}} \tag{15}$$

Thermal efficiency of solar collector can be determined by following equation [56]:

$$\eta_c = \frac{m_o(T_{out} - T_{in})}{I_s A} \times 100\% \tag{16}$$

Whereas the drying efficiency of forced convection dryer may be estimated by following expression [57]:

$$\eta_d = \frac{WL}{I_c A + P_f} \times 100\% \tag{17}$$

Also, the pickup efficiency (or moisture removing efficiency) of drying air is given as follows [57]:

$$\eta = \frac{h_o - h_i}{h_{as} - h_i} \times 100\% \tag{18}$$

3.2. Exergy analysis

In exergy analysis, the terms (momentum, gravity and chemical reactions) may be neglected for the simplicity of process analysis. However, radiation emission which highly depends on temperature conditions should be considered particularly for exergy analysis. Midilli and Kucuk [58] presented energy and exergy analyses of solar drying of shelled and unshelled pistachios (Pistacia vera) at temperature (40–60 °C), solar radiation (200–808 Wm^{-2}) and drying air velocity (1.23 ms^{-1}). The energy consumption and exergy losses were identified to be more in unshelled pistachios than shelled pistachios. The exergy measurements were carried out by using Eq. (19) [59].

$$Ex = C_p\left[(T - T_\infty) - \frac{T_\infty \ln T}{T_\infty}\right] \quad (19)$$

Overall, exergetic efficiency of 100% was reported for zero exergy losses at the completion of drying process. Another study Celma and Cuadros [60] presented energy and exergy analyses of a natural convection indirect solar dryer for drying olive mill wastewater and reduced its moisture from 3.153 to 1.000 $g_{water}/g_{dry\ matter}$ at temperature (34–52 °C), relative humidity (58%), solar radiation (227–825 W/m^2) and air flow velocity (0.036–0.042 kg/s). The exergy losses (0.17 kJ/kg) were occurred more during second day of drying. Overall, exergetic efficiencies for first and second day of drying were reported to vary from 53.2% to 100.0% and 34.4–100.0%, respectively. The expression used for exergy calculation is given in Eq. (20) [61].

$$\dot{Ex} = \dot{m}_{da} C_p\left[(T - T_0) - T_0 \ln\left(\frac{T}{T_0}\right)\right] \quad (20)$$

Akpinar [62] also presented the exergetic performance of solar drying of mint leaves (Mentha) by using the following expression.

$$\sum\left(1 - \frac{T_\infty}{T}\right)\dot{Q} - \dot{W} + \sum \dot{m}_i \psi_i - \sum \dot{m}_o \psi_o = \dot{Ex}_d \quad (21)$$

Maximum exergy efficiency of 87.7% was found, however, the author did not find any significant difference in drying quality for solar drying and OSD. Whereas in another study, Akpinar et al. [63], the maximum input exergies for first and second day of drying were observed to be 0.345 and 0.272 kJ/kg, respectively. The expression used for exergetic analysis is given in Eq. (22).

$$\varepsilon = 1 - \frac{\dot{E}_{loss}}{\dot{E}_{in}} \quad (22)$$

The exergy variations inside the drying chamber observed in some studies is depicted in Fig. 4.

3.3. Case studies

Bolaji [64] presented exergetic analysis of three solar dryers (direct, indirect and mixed modes) under same environmental conditions. Energy conversion and exergetic efficiencies of direct, indirect and mixed modes solar dryers were reported to be 78.1% and 33.7%, 77.0% and 54.5% and continue 49.3% and 55.2%, respectively. Therefore, mixed and indirect modes were reported more efficient and suitable in energy utilization than direct mode solar dryer. Icier et al. [65] compared the energetic and exergetic performance of two different drying systems (tray dryer and fluid bed dryer) for drying parsley (Petroselinum crispum). Drying in fluid bed dryer (having air velocity of 3.7 m/s) was faster than tray dryer (having air velocity of 1.5 m/s), however, exergy efficiency of latter was investigated more than former for drying temperature of 40–60 °C. Therefore, higher air temperature and lower velocity resulted in higher energy and exergy efficiencies of both dryers. Akinola and Fapetu [66] evaluated the exergetic performance of a mixed mode dryer for drying pepper (Piper nigrum), yam (Dioscorea alata), water leaf (Talinum triangulare) and okra (Abelmoschus esculentus).

The overall exergy efficiency and thermal efficiency were obtained to be 56.0% and 66.9%, respectively. However, a significant waste (44.0%) of energy was also reported in drying process. Moreover, the dryer was more effective than direct sun drying. Chowdhury et al. [67] experimentally studied the energetic and exergetic performance of solar tunnel dryer for drying jackfruit leather and reduced its moisture from 76.0% to 11.8% (w.b.) in two days of drying. However, OSD reduced moisture up to 13.8% (w.b.) in same drying time. For solar irradiance of 100–600 Wm^{-2}, the average energy and exergy efficiencies of dryer were obtained to be 42.5% and 41.4%, respectively. Fudholi et al. [68] designed and developed a forced convection indirect solar dryer for drying red seaweed (Rhodophyta) and reduced its moisture from 90.0% to 10.0% (w. b.) in 15 h (at solar radiation of 500 Wm^{-2} and air flow rate of 0.05 kg/s). The collector, drying and pick up efficiencies were obtained to be 35.0%, 27.0% and 95.0%, respectively. Whereas the average exergy efficiency and improvement potential of dryer were observed to be 30.0% and 247.0 W, respectively. The page model was best suited for describing the drying characteristics of red seaweed. The schematic view of forced convection indirect solar dryer is shown in Fig. 5.

Akpinar and Sarsilmaz [69] presented energy and exergy analyses of rotary column cylindrical dryer for drying apricots (Prunus armeniaca) at drying temperature (38.0–57.8 °C), relative humidity (20.5–49.7%), drying air velocity (2.3 ms^{-1}) and column rotary speed (2.25 rpm). The highest exergy losses of 0.5612 kJ/kg were reported in 76 h of drying. Mokhtarian et al. [70] investigated energetic and exergetic performance of three drying methods (solar dryer with air recycling-method I, solar dryer without air recycling-method II and sun drying-method III) for drying pistachio (Pistacia vera) and reduced its moisture from 40.0% to 5.0% (w.b.). As compared to method II, thermal efficiency (40.0%) and pick-up efficiency (80.0%) of method I were reported higher.

Although the exergy efficiencies of both method I and method II were observed to be same (~95.0%) but the exergy losses in method I were found higher due to high air temperature and pressure losses. Further, the energy utilization ratio of method I (50.0%) was also investigated to be more than method II (30.0%) and method III (20.0%), however, the drying rate was 20.0% less than method II and 30.0% than method III. Hadi et al. [71] carried out energy and exergy analyses of forced convection solar dryer for drying tomato (Solanum lycopersicum) at drying temperature (22.0–36.0 °C), relative humidity (14.0–50.0%), solar radiation (150.0–850.0 Wm^{-2}) and air flow rates (0.5–1.0 ms^{-1}). For sample thickness of 5.0 mm and air flow rate of 1.0 ms^{-1}, the values of energy utilization (6.6–152.7 W), energy utilization ratio (0.02–0.45), exergy loss (2.4–32.0 W) and exergy efficiency (32.0–80.0%) were calculated. The energy utilization rate and exergy loss efficiency of drying chamber were observed to decrease with increase in air flow rate and drying thickness, however, exergy efficiency and energy utilization were found to be increased.

Panwar [72] experimentally studied energetic and exergetic performance of natural convection solar dryer for thin layer drying of coriander (Coriandrum sativum L.) and reduced its moisture from 88% to 4.5% (w.b.) in 7.5 h. Energy and exergy efficiencies of dryer were reported to vary from 7.8% to 37.9% and 55.4–79.4%, respectively. In addition, the drying model suggested by Midilli et al. [10] was best suited for describing the drying characteristics of coriander. Akbulut and Durmus [73] investigated energy and exergy analyses of forced convection solar dryer for thin layer drying of mulberry (Morus). The energy utilization ratio (20.5–55.2%) and exergy losses (2.6–10.8 W) were observed to decrease with increase in mass flow rates from 0.014 to 0.036 kg/s. The schematic view of forced convection solar dryer is shown in Fig. 6.

Doblada et al. [74] presented energy and exergy analyses of solar

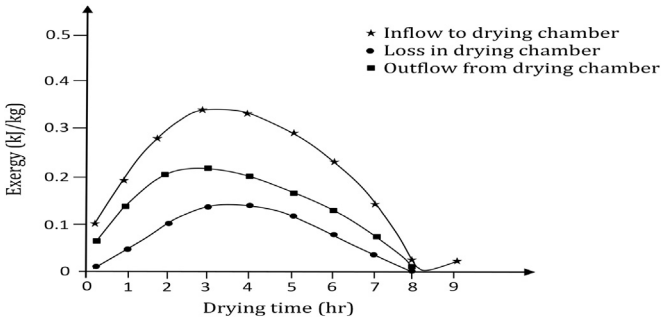

Fig. 4. Exergy variations inside the drying chamber [60].

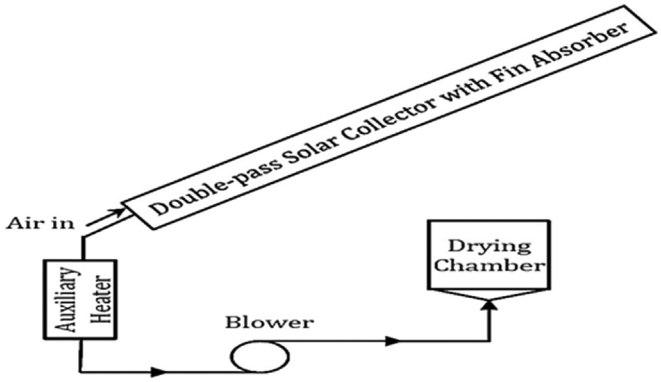

Fig. 5. Forced convection indirect solar dryer [68].

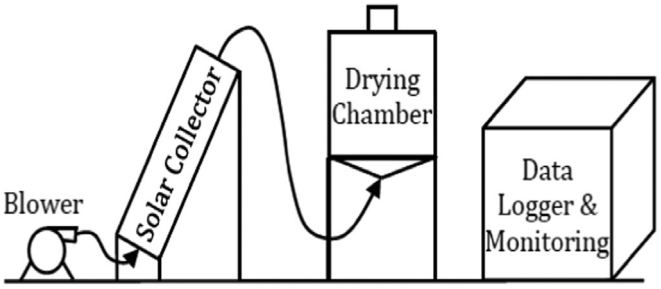

Fig. 6. Forced convection solar dryer [73].

dryer for drying microalgae (Pediastrum boryanum) and reduced its moisture from 90.0% to 10.0% in 5 h for biodiesel production. The energy and exergy efficiencies were reported low as 1.5% and 28.0%, respectively. The fact of obtaining low efficiencies can be understood due to small sample size, high temperature of inlet air and high humidity ratio inside the drying chamber.

Among different solar drying systems, the active (or forced) indirect and hybrid dryers are the promising methods with enhanced thermal performance and quality drying of product. Besides, the mixed flow dryers having high energetic and exergetic performance are also in recent trends. The energy and exergy efficiencies of such dryers are reported to be 78.1% and 56.0%, respectively. The collector unit is observed to have the highest exergy losses and thus it has high exergy improvement potential (236.0–551.6 W). Also, the conversion of high grade energy from auxiliary heating devices to low exergy requirements (like drying) leads to low exergy efficiency of the entire process. The overall performance of drying system can be improved by minimizing the energy losses through certain techniques (plane reflector, recirculation of drying air, thermal storage and design augmentation in collector unit) and optimizing process parameters (sample thickness, drying air temperature, flow rate and humidity ratio).

4. Solar refrigeration and air conditioning

Energy demand especially for cooling applications in commercial and residential buildings is continuously escalating due to rapid increase in population worldwide. The International Institute of Refrigeration (Paris, France) has reported that the refrigeration consumes around 15.0% of the total electricity generation in domestic and industrial applications, globally. Whereas the air conditioning has outlined to consume approximately 45.0% of the total residential energy consumption [75,76]. Thus, the solar refrigeration and air conditioning can be a sustainable solution to deal with vital problems of energy crisis in cooling and heating applications. Generally, these systems include NH_3-H_2O, LiBr-H_2O absorption and adsorption refrigeration. Each refrigeration system requires different operating temperature conditions to be fulfilled by optimally designed solar heat sources [77]. The LiBr- H_2O absorption refrigeration systems are widely used in cooling applications where evaporation temperatures are required to vary from 5.0 to 10.0 °C. However, these systems are not effective for the very low evaporation temperature (below 0 °C). Whereas NH_3-H_2O refrigeration systems are developed to work in low operating temperature conditions and have wide scope in small size air conditioning and other large industrial applications [78].

Further, LiBr- H_2O absorption cooling is also subjected to the risk of crystallization and attributed to increase the absorber temperature and thus have confined use in residential scale applications. However, NH_3-H_2O absorption is free from crystallization because ammonia has very low freezing temperature and do not crystallize at low evaporator temperature. Besides, it is more compact due to low specific volume of high pressure refrigerant. Therefore, the requirements of cooling capacity (3.0–10.0 kW) for residential space can easily be met by NH_3-H_2O absorption system at low cost [79,80]. Overall, solar thermal cooling is capable of reducing the energy demands during peak hours in summer by utilizing thermal driven chillers in place of high energy consuming electrically driven compressor chillers. But, these systems are also suffering from several bottlenecks including the low energy and exergy performance and hence, an opportunity can be taken up to improve their overall performance for different load

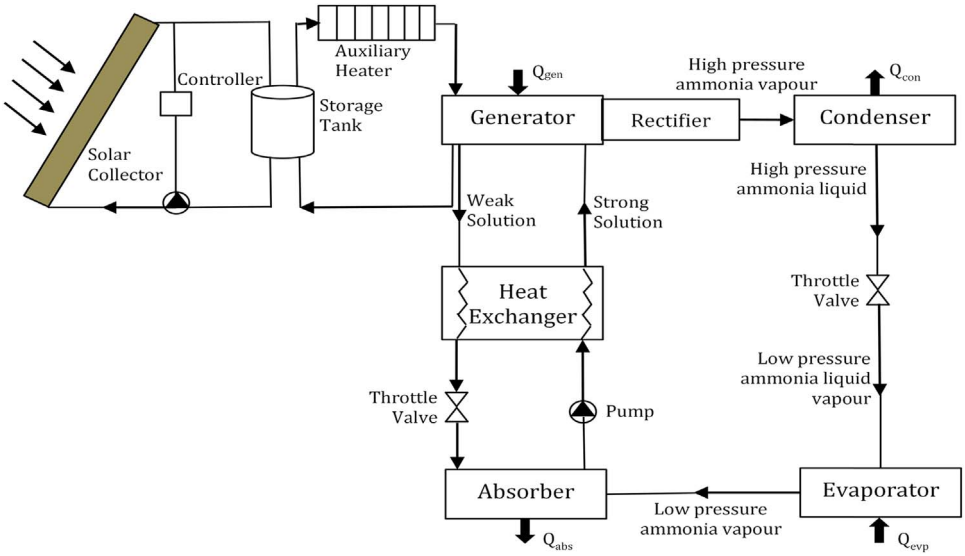

Fig. 7. Solar NH_3-H_2O absorption system [49].

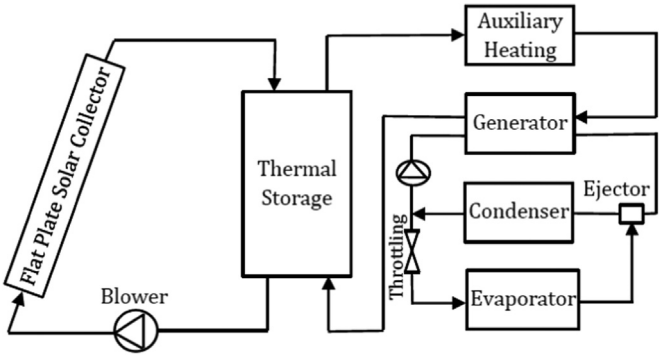

Fig. 8. Solar driven ejector refrigeration [89].

requirements. The small-scale industries can also make efforts in optimum designing of low cost compact devices with higher COP values at low temperature conditions [81].

4.1. Energy analysis

The energy and exergy analyses of an ammonia absorption based air conditioning system were carried out by [49] using first and second law of thermodynamics. In first law analysis, following principle equations and schematic system (Fig. 7) were used to determine the mass and energy conservation for different components of the system.

The mass and energy conservation equation may be written as follows [49]:

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = 0 \tag{23}$$

$$\sum \dot{Q} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} + \dot{W} \tag{24}$$

Whereas the overall performance of the system is represented in term of coefficient of performance (COP) [82], i.e.

$$COP = \frac{\text{Useful energy gain}(\dot{Q}_{eva})}{\text{Energy supply in generator}(\dot{Q}_{gen}) + \text{Work done by pump}(\dot{W}_P)} \tag{25}$$

4.2. Exergy analysis

Pridasawas and Lundqvist [83] presented exergy analysis of a refrigeration system (comprised of evaporator, pump, generator, condenser and ejector) under optimum operating conditions of temperature, pressure and flow rates. Thus, the exergy balance obtained from the system is given as follows:

$$Ex_{s,h} + Ex_e + W_{p,el} = Ex_{c,out} + I_{total} \tag{26}$$

Where $Ex_{s,h}$ is given by [84]:

$$Ex_{s,h} = Q_m\left(1 - \frac{T_a}{T_m}\right) \tag{27}$$

The exergy efficiency of 0.66% was calculated for solar collector which was observed to be the main source of irreversibility. Another study [85] investigated maximum exergy efficiency of 11.9% for solar assisted absorption cooling system under standard and ambient temperature conditions by using same expressions as given in Eqs. (21) and (22).

4.3. Case studies

Baiju and Muraleedharan [86] investigated energetic and exergetic performance of solar hybrid adsorption refrigeration designed for heating (50 l) and cooling (10 l) of water from 25.0 to 90.0 °C and 25.0–10.0 °C, respectively. For cooling capacity of 47.0–48.0 W, the maximum and minimum values of COP were reported to be 0.45 and 0.19, respectively. Adsorbent bed was observed to be the major source of irreversibility and caused inefficient utilization of heat energy due to material constraints. The exergetic efficiencies of condenser (42.3%), expansion device (79.8%), evaporator (54.7%) and adsorbent bed (11.0%) were also obtained. Khaliq et al. [87] investigated energy and exergy analyses of solar driven triple staged refrigeration cycle integrated with absorption refrigeration cycle, ejector refrigeration cycle (ERC) and ejector expansion Joule-Thomson (EJT) refrigeration cycles. The effects of several design parameters (outlet temperature of hot oil, evaporator temperature of ERC, inlet pressure of refrigerant turbine and EJT) on energy and exergy performance of the system were evaluated. Major sources of irreversibility were central receiver (52.5%) and heliostat field (25.0%), followed by condenser and ejector. The overall energy and exergy efficiencies of the system were obtained to be 10.0% and 4.0%, respectively. Grosu et al. [88] evaluated the performance of a solar cogeneration system having combined cycle of organic Rankine cycle (ORC) and absorption cooling system (using LiBr-H_2O) for electricity supply and cooling of an academic building (Paris, France). The exergetic efficiency of ORC was reported to decrease with increase in exergy resource (fuel) and temperature of water and thus caused higher irreversibility in solar heat exchanger. Therefore, a recovery heat exchanger at the inlet of condenser was suggested to improve the system performance.

Jain et al. [89] presented exergy analysis of a solar driven ejector refrigeration (For cooling capacity of 5 kW, solar radiation of 700 W/m^2, evaporator temperature of 10.0 °C and ambient temperature of 30.0 °C). The overall thermal efficiency (5.8%), COP (0.13), solar

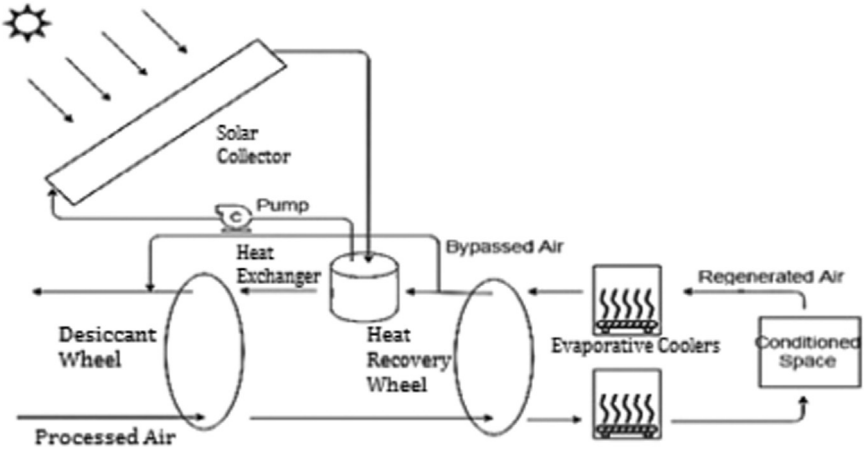

Fig. 9. Desiccant cooling system [93].

energy efficiency (35.0%) and refrigeration cycle efficiency (22.0%) were calculated. Highest exergy losses were found in solar collector (31.3 kW) whereas the total exergy losses of 3.1 kW were reported in refrigeration cycle. The schematic view of solar driven ejector refrigeration is shown in Fig. 8.

Golchoobian et al. [90] investigated exergy analysis of solar ejector refrigeration system (using R141) for air conditioning of building in Tehran (Iran). A significant improvement in exergetic performance of the system was observed using hot water storage tank. Higher exergy losses were also observed in collector followed by ejector. Overall, system irreversibility was found more during first and last working hours. Kaynakli and Yamankaradeniz [91] developed a mathematical model to study the thermodynamics performance of absorption refrigeration system (using LiBr-H_2O) in the climate conditions of Bursa (Turkey). The system performance was observed to increase with decrease in condenser-absorber temperatures and increase in generator-evaporator temperatures. Besides, the value of COP was also reported to increase with decrease in pumping energy (on account of increasing generator temperature). Overall, second law analysis of power and energy system was suggested as useful tool in analysis of engineering design and optimization.

Kanoglu et al. [92] presented energy and exergy analyses of an open cycle desiccant cooling (using natural zeolite as desiccant) in the climate conditions of Gaziantep (Turkey). The COP (0.35), reversible COP (3.11) and exergy efficiency of the system (11.1%) were calculated. Highest exergy losses were found in desiccant wheel (33.8%) followed by heating system (31.2%). A reversible COP approach was suggested to minimize the exergy losses in the system. However, the techno-economic analysis of system was absent in the study. Rafique et al. [93] performed the energy, exergy and anergy analyses of a desiccant cooling system operated on ventilation cycle in the climate conditions of Saudi Arabia. The effect of exergy transportation, destruction, temperature and ratio of generation to process air flow rate on the performance of the system was studied. Highest exergy losses of 65.0% were reported in desiccant wheel and solar collector. The schematic view of desiccant cooling system is shown in Fig. 9.

Rosiek and Batlles [94] studied solar powered air conditioning (comprised of a FPC and LiBr-H_2O absorption chiller) for cooling the building of Solar Energy Research Centre, Spain. The value of COP (0.6) was calculated for different temperature conditions of generator, absorber, condenser and evaporator.

Kaushik et al. [95] experimentally studied energetic and exergetic performance of solar PV driven thermoelectric cooler (cooling capacity of 500 ml of water) for cold storage application require temperature range of 13.0–16.0 °C. Overall, the cooling power, energy and exergy efficiencies were observed low but can be improved by using thermoelectric materials. The schematic view of solar PV driven thermoelectric cooler system is shown in Fig. 10.

Ahmed et al. [96] presented exergy analysis of liquid desiccant hybrid air conditioning having solar generator for regenerating weak desiccant. Overall performance of the system was observed to decrease due to high irreversibility occurred at ambient vapour pressure (25 mm Hg) and desiccant mass flow rate (5 kg/h.m^2). An optimum mass flow rate (30 kg/h.m^2) was also calculated to minimize the exergy losses in the system. Chinnappa et al. [97] studied energy analysis of a hybrid air conditioning system having a conventional R-22 vapour compressor refrigeration cascaded with solar operated vapour absorption system (NH_3-H_2O). The condenser of R-22 system was cooled by evaporator of ammonia system and reduced the condensing temperature and pressure to save energy. Bouaziz and Lounissi [98] developed a thermodynamics model to study energetic and exergetic performance of solar assisted hybrid absorption refrigeration (using NH_3-H_2O combination). The COP (21.0%), exergy efficiency (~28.7%) and irreversibility (~4.3 kW) of whole system were evaluated. Overall performance of the system (operated at 60–120 °C) was observed higher than two-stage conventional configuration (operated at 100–160 °C).

Gunhan et al. [99] evaluated the exergetic performance of a solar assisted LiCl-H_2O absorption cooling system and reported exergy efficiency of 13.1–43.2% at temperature range of 30–42 °C. At dead state temperature of 34 °C, the highest irreversibility in solar collector and absorption chiller were obtained to be 66.1% and 34.6%, respectively. The schematic view of solar assisted LiCl-H_2O absorption cooling system is shown in Fig. 11.

Siddiqui et al. [100] presented exergo-economic analysis of solar driven absorption refrigeration (cooling capacity of 5 kW) with hybrid storage system (comprised of cold storage tank, ammonia storage tank, weak and strong solution tank) in the climate conditions of Dhahran (Saudi Arabia). The exergo-economic and quasi state analyses of different components of the system were carried out in terms of relative cost difference, exergy destruction cost rate and exergo economic factor. Compared to morning/evening time, the exergetic efficiency and exergo-economic factor were observed to decrease more in noon time. Optimization of system design parameters was recommended to obtain the cost-effective process. Performance characteristics of different working fluids for adsorption refrigeration is depicted in Table 2.

Due to higher COP and cost savings, the LiBr-H_2O are generally used for solar air conditioning purposes, however, it crystallizes during operation and increase the absorber temperature. Whereas other refrigerant-absorber combinations like LiCl-H_2O, $CaCl_2$-H_2O and NH_3-H_2O (free from crystallization) are also commonly used, depending on the cooling requirements. The typical values of COP for these

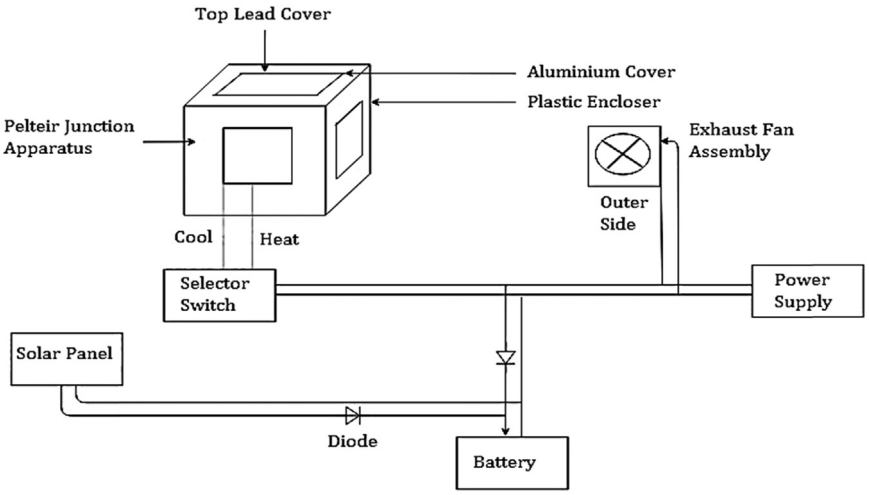

Fig. 10. Solar PV driven thermoelectric cooler [95].

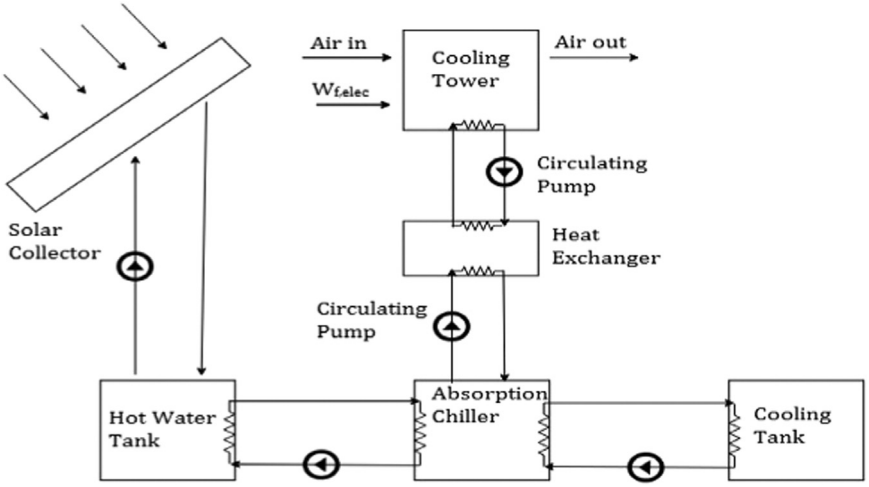

Fig. 11. Solar assisted LiCl-H_2O absorption cooling system [99].

Table 2
Performance characteristics of various working fluids [101].

Working fluids	COP (Max)	T (°C)	Mass fraction (% weight)	Density (kg/m^3)	Viscosity (kg/m.s)	Specific heat (kJ/kg °C)
LiCl-H_2O	0.83	85.0	49.48	1368.0	0.350	2.70
LiBr-H_2O	0.81	85.0	39.60	1682.0	4.598	1.89
$CaCl_2$-H_2O	0.79	89.4	54.74	1464.0	0.147	2.38
NH_3-$LiNO_3$	0.71	91.1	45.35	1027.0	1.307	2.99
NH_3-NaSCN	0.63	105.0	39.85	1006.0	1.111	2.61
NH_3-H_2O	0.53	120.0	31.23	64.2	0.174	4.19

systems are observed to vary from 0.5 to 0.8. While the energy and exergy efficiencies of different solar refrigeration and air conditioning systems are found to vary from 5.8% to 35.0% and 4.0–11.0%, respectively. However, the working performance can be enhanced by minimizing energy losses in collector, condenser and evaporator units through optimization and simulation techniques. Also, the installation cost particularly for the requirement of larger collector array is high and thus cause barrier in their commercialization.

5. Solar water heating

Solar water heating is the most popular and attractive means of solar energy utilization in domestic and industrial sector. Economic and technological feasibility of these systems have also been observed to be significantly high [51]. In general, solar water heating is comprised of mainly two elements namely, the collector unit and storage with insulation. Collector unit consists of an absorber panel coated with selective material to absorb solar energy and transfer heat to water flowing through tube and gets stored in an insulated storage tank for end use applications [102]. Solar water heating systems can be classified into two broad categories namely, active and passive systems. An active system receives required heat for water heating directly from solar energy while the passive systems require heat transfer medium for effective heating. Therefore, passive water heating has large scope of improvement in their convective heat transfer characteristics. Many researchers have studied the working performance of different water heating systems and reported the general rise of water temperature up to 60–70 °C [103]. However, higher range of temperature can be achieved through solar concentrators for high temperature applications (steam cooking and power generation).

Chandavar et al. [104] designed and developed a CPC for rice cooking during night hours. The maximum temperature of thermic fluid (Duratherm 630) was reported to be around 110 °C. However, during off-sunshine hours, it was observed to be lower as 35 °C, though sufficient for rice cooking. Overall, maximum efficiency of the system was obtained to be lower around 32.3% due to inclemency of climate throughout the day. Whereas in another study [105], the temperature of hot water for domestic use was recorded as 70.3 °C and 59.5 °C at the bottom of hot water tank. The overall system and collector efficiency was calculated to be 52.0% and 63.2%, respectively. However, pipe losses of 17.7% of total energy collected and 21.5% of energy delivered to hot water tank were also reported. Therefore, energetic and exergetic performance of these systems can be further improved through various heat transfer enhancement techniques (improving collector design, using thermal energy storage, thermal insulation, phase change materials etc.). Design optimization and simulation are also very important tools to study the working performance of different components of solar water heating [103].

5.1. Energy analysis

The useful energy or energy absorbed by water in storage tank may be obtained as follows [106]:

$$Q_w = Q_c - Q_b - Q_l \tag{28}$$

Whereas the useful energy stored by water (Q_w), body (Q_b) and energy losses (Q_l) can be calculated as follows [106]:

$$Q_w = m_w C_{pw}(T_{fin} - T_{ini}) \tag{29}$$

$$Q_b = m_b C_b(T_{fin,b} - T_{ini,b}) \tag{30}$$

$$Q_l = U_L(T_m - T_a) \tag{31}$$

Thus, the energy efficiency of solar water heater can be obtained from Eq. (29) and is given as follows [106]:

$$\eta = \frac{m_w C_{pw}(T_{fin} - T_{ini})}{AI_s} \tag{32}$$

5.2. Exergy analysis

The collector exergy of solar water heating can be calculated based on its configuration and is given as [107,108]:

$$Ex_c = AI_s\left[1 - \left(\frac{T_a}{T_s}\right)\right] \tag{33}$$

Whereas the exergy received by water in storage tank may be written as

follows [107,108]:

$$Ex_w = \dot{m}C_{p,w}(T_o - T_i)\left(1 - \frac{T_a}{T_w}\right) \quad (34)$$

Hence, the overall exergy efficiency obtained from Eq. (33) and Eq. (34) is given as [107,108]:

$$\varepsilon = \frac{Ex_w}{Ex_c} = \frac{\dot{m}C_{p,w}(T_o - T_i)\,[1 - (T_a/T_w)]}{I_s A[1 - (T_a/T_s)]} \quad (35)$$

5.3. Case studies

Pandey et al. [109] evaluated the performance of a ETC water heater in terms of energy, exergy and other process parameters (fuel depletion ratio, relative irreversibility, productivity and exergetic lack) for different volume flow rates (10–30 l per hours). Performance of the system was reported to be maximum and minimum at 15 and 30 l per hours, respectively. However, the energy efficiency of the system was observed to be higher than exergy efficiency for all volume flow rates. Johari et al. [110] presented exergy analysis of various solar water heaters and observed highest exergy losses in conversion of solar radiation into the useful heat energy. An improved design of storage tank was also endorsed since storage tank claims the highest exergy losses. Further, the design optimization was also recommended to reduce the exergy losses involved in various conversion devices. Liu et al. [111] also reported highest exergy destruction (99.3%) in collector unit of solar water heating system. Whereas in thermal storage, the exergy losses were small due to heat transfer interactions (0.39%) and air to water heat exchanger (0.12%). However, the combined exergy destructions (thermal storage + heat exchanger) were found to be second highest to solar collector. Exergy destructions due to friction in air flow (0.08%), air flow mixing (0.04%) and water storage tank (0.02%) were also calculated.

Kargarsharifabad et al. [112] investigated exergy analysis of pulsating heat pipe flat plate collector (PHPFPC) for water heating in the climate conditions of Tehran (Iran). As compared to the conventional collectors, the exergy efficiency of PHPFPC was reported to be higher as 10.0% and have negligible exergy destructions due to pressure drop. The exegetic performance of the system was expected to improve using optimum insulating materials, higher transitivity glass and thermal break frames. Ayompe et al. [113] compared the energy performance of flat FPC (4 m^2) and ETC (3 m^2) for water heating in the climate conditions of Dublin (Ireland). For annual solar insolation of 1087 $kWhm^{-2}$, the heat energy collected by FPC and ETC were calculated to be 1984 and 2056 kWh, respectively. The average FPC efficiency (46.1%) and ETC efficiency (60.7%) were also calculated along with corresponding system efficiencies (37.9% for FPC and 50.3% for ETC). However, both systems were not reported economically viable due to higher present values (-€4264 - €652) and payback periods (13.0–48.5 years). Xiaowu and Ben [114] presented exergy analysis of domestic size solar water heater and observed highest exergy losses in storage system. Exergy losses due to imperfect insulation in collector and storage unit were significant and thus can never be ignored. Therefore, proper selection of plate width and thermal insulation were examined to be an important design criterion to minimize the exergy losses. The schematic view of domestic size solar water heaters is shown in Fig. 12.

Hayek et al. [115] experimentally studied exergetic performance of water heating with two ETC's (viz. water-in-glass and heat pipe). The heat pipe based ETC claimed higher efficiency (15–20%) as compared to water-in-glass based ETC. However, payback period of the former was higher than the latter, owing to high initial investment cost. Gang et al. [116] investigated exergetic performance of CPC water heater in the climate conditions of Hefei (China). Overall thermal efficiency of the system was reported to vary from 43.0% to 49.0% for water tank temperature of 26.9–95.0 °C. Whereas the maximum exergetic efficiency was obtained to be 4.6% at 55 °C water temperature. Moreover, the system was observed to have the satisfactory thermal performance at high temperature conditions. Jegadheeswaran and Pohekar [117] developed a particle (copper) dispersed latent heat thermal storage for solar water heating and investigated its exergetic performance using computational fluid dynamic technique. For particle volume fraction of 0.1, the exergy efficiency, total exergy recuperation and reduction in discharging time were observed to be 12.0%, 15.0% and 28.0%, respectively while for particle volume fraction of 0.4, it was found to be 50.0%, 60.0% and 85.0%, respectively. However, reduction in discharging time was not reported appreciable after particle volume fraction of 0.4.

Tiwari et al. [118] investigated exergetic performance of PV/T water heater based on the energy balance approach. Thermal efficiency of the system was found to increase with increase in constant flow rate and decrease with increase in constant collection temperature. For hot water flow rate of 0.006 kg/s, the exergy efficiency (~9.15–14.0%) and thermal efficiency (~50.0–64.0%) were reported to be maximum. The schematic view of solar PV/T water heater is shown in Fig. 13.

Hong et al. [119] investigated exergy analysis of a coal-fired power plant integrated with low-grade solar heat for feed water heating. Exergy efficiency of hybrid system was estimated to be 38.5% against the exergy efficiency of 37.3% for traditional coal fired plant. While the overall solar to electricity efficiency of the system was obtained to be above 15.0% which was however, calculated to be 1.4–5.7% for partially repowered system. The work output was also observed to increase from 136.7 to 153.8 MWe, however, solar collector also claimed an increase in capital cost to $2007/kWe.

Yousefi and Moradali [120] experimentally studied the thermodynamics performance of a direct expansion solar assisted heat pump (comprised of FPC, water tank and condenser) for water heating. The value of COP was obtained to be 6.4 (at solar irradiations of 450 W/m^2, compressor speed of 1100–1700 rpm and ambient temperature of 15 °C) and was reported more than conventional heat pump water heater. Walker and Davidson [121] presented exergy analysis of two phase self-pumping solar water heater under Solar Rating and Certification Corporation Rating conditions for the climate conditions of Colorado (USA). Total entropy generation accounted for collector (87.1%), thermal losses (9.9%), condenser heat transfer (2.4%) and mixing in tempering valve (0.7%) were calculated. However, half of the entropy generation due to thermal losses resulted in self-pumping process. Tabook et al. [122] carried out thermal and electrical performance of solar PV/T system (in terms of solar cell temperature, inlet and outlet air temperature, maximum power current and voltage, open circuit voltage, short circuit current and air mass flow rate) for water and air heating. For solar irradiance of 350–800 W/m^2, the

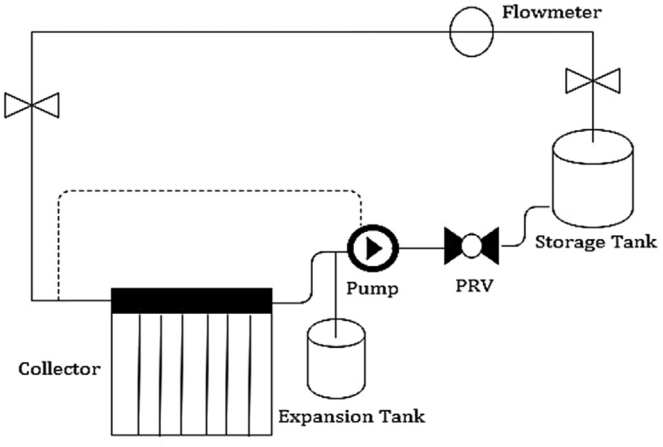

Fig. 12. Domestic size solar water heater [114].

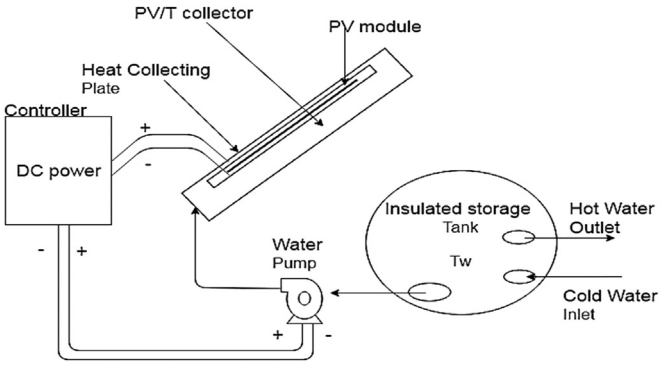

Fig. 13. Solar PV/T water heater [118].

thermal, electrical and overall energy efficiencies of the system were obtained to be 15.4%, 18.0%, 18.3% and 18.9%, respectively. The schematic view of solar PV/T for water and air heating is shown in Fig. 14.

Daghigh and Shafieian [123] investigated energetic and exergetic performance of a multipurpose evacuated tube heat pipe for water heating and drying purposes. The maximum temperatures of water and air obtained were 56.3 and 45.5 °C, respectively. Highest exergy destructions of 95.0% were observed in solar collector and so plays an important role in improving the exergy efficiency of the system which was initially reported to be around 10.6%. The uncertainties related to exergy efficiency (± 4.8%), thermal efficiency (± 5.1%), wind velocity (± 1.2%), temperature (± 2.5%) and solar radiation (± 3.8%) were also calculated. Mahfuz et al. [124] investigated energy and exergy analyses of thermal energy storage having paraffin as phase change material for water heating. For water flow rates of 0.03 kg/min, the energy and exergy efficiencies were calculated to be 63.8% and 9.6%, respectively while for water flow rates of 0.17 kg/min, it was obtained to be 77.4% and 6.0%, respectively. The total life cycle costs of $654.6 and $609.2 were also reported for the same water flow rates (i.e. 0.03 and 0.17 kg/min, respectively). The schematic view of thermal energy storage system is shown in Fig. 15.

In another study, Daghigh and Shafieian [125] also studied the thermal performance of ETC water heater. The exergetic efficiency was observed to increase with the progression of day and reported to be around 5.4% at the end of day. The relative error (8.4%) and standard error (1.9%) were also calculated while validating theoretical results with experimental.

The ETC in combination with heat pipe are in recent trend for efficient water heating because of low cost and improved performance. However, more studies are required to investigate them in terms of exergetic performance, techno-economic feasibility and social adaptability. The thermal, energy and exergy efficiencies of different water heating systems are observed to vary from 15.4% to 49.0%, 63.8–77.4% and 6.0–9.6%, respectively (for different water temperature requirements, mass flow rates and solar irradiance). The highest exergy losses are found in collector and storage tank and thus a higher exergy improvement potential can be expected through design optimization. The use of copper particles in thermal energy storage is helpful in enhancing the heat transfer conditions and reducing the discharge time. However, care should be taken in size selection of cooper particles to attain the uniform heat transfer characteristics. Further, the use of waste heat from thermal power plants can also save energy for water heating applications.

6. Solar cooking

Cooking is the major necessity for people across the world. However, the high cost of fuel and diminishing supply of firewood for cooking applications have raised the need of alternative energy solution, especially in developing countries. Solar cooking is capable of substituting the cooking practices utilizing conventional fuels (firewood, agricultural wastes and animal dung). It not only conserve fossil fuels but also improves the living standards of community by providing standard cooking practices, high nutrients food and eco-friendly environment [126]. In general, solar cookers are divided into two categories viz. concentrating (or focusing) type and box type. The concentrating (or focusing) type solar cookers are based on the principle of concentration of solar energy on cooking vessel through reflector [127,128]. Whereas the box type solar cookers utilize greenhouse effects in combination with some solar concentration. The first person who developed box type solar cooker in 1767 was a Swiss naturalist named Horace de Saussure [129–132].

They are simple in design, cost effective and widely used in cooking rice, vegetables, meat and other items. But, the cooking time required in them is high (1–2.5 h) and also unable to perform satisfactorily in winter and at heavy cooking load conditions [133]. On the other hand, the concentrating solar cookers requires small cooking time and speedily cooks the items even with high moisture levels. The concentrators (like parabolic and Scheffler dishes) are based on line or point focus arrangement and requires one or two axes tracking for various cooking applications. As compared to box types, the concentrating solar cookers are capable of achieving the higher temperature conditions due to sharp focus. Therefore, solar steam cooking is a technological advancement with high cooking potential around the year. However, the working performance of these systems is required to be investigated thoroughly in different aspects of energy and exergy analyses to study their design optimization, thermodynamics and economic values [134].

6.1. Energy analysis

The energy output of solar cooking system may be calculated as follows [102]:

$$E_o = \frac{mC_p(T_{fin} - T_{ini})}{t} \quad (36)$$

While the energy efficiency of solar cooking system is given as follows [102]:

$$\eta = \frac{E_o}{E_i} = \frac{mC_p(T_{fin} - T_{ini})/t}{I_s A} \quad (37)$$

6.2. Exergy analysis

The exergy balance of solar cooking system for steady state flow conditions is given as follows [135–137]:

$$Ex_{in} = Ex_{out} + Ex_{loss} + \text{irreversibility} \quad (38)$$

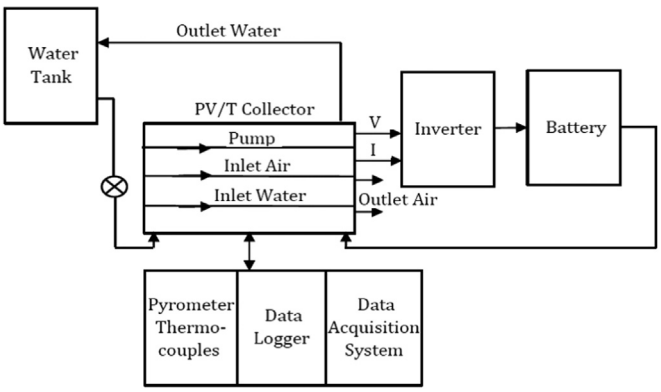

Fig. 14. Solar PV/T for water and air heating [122].

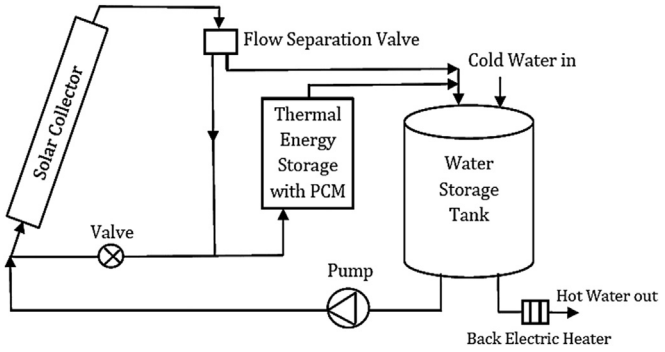

Fig. 15. Thermal energy storage system [124].

The exergy input of solar cooker is given by the following expression [135–137]:

$$Ex_{in} = i\left[1 + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)\right]A_{sc} \quad (39)$$

Whereas the exergy output of solar cooking system is expressed as follows [135–137]:

$$Ex_{out} = mC_p\left[(T_{fin} - T_{ini}) - T_a \ln\left(\frac{T_{fin}}{T_{ini}}\right)\right]/\Delta t \quad (40)$$

Thus, the exergy efficiency of solar cooking system can be obtained from Eq. (39) and Eq. (40) [135–137] i.e.

$$\varepsilon = \frac{Ex_{out}}{Ex_{in}} = \frac{mC_p\{(T_{fin} - T_{ini}) - T_a \ln(T_{fin}/T_{ini})\}/\Delta t}{i\{1 + (1/3)(T_a/T_s)^4 - (4/3)(T_a/T_s)\}A_{sc}} \quad (41)$$

6.3. Case studies

Pandey et al. [137] compared exergetic performance of two solar cookers (paraboloid and box type) for different volume of water (one and two litres) along with the rice. The exergy efficiencies of paraboloid type solar cooker were reported higher than box type and obtained to be 7.1% and 10.4% for one and two litres of water, respectively. However, due to different heating requirements of food stuff, the exergy efficiency was observed to vary with cooking stuff and volume of water contemplated. Panwar [138] carried out energy and exergy analyses of an animal feed solar cooker. The experimental values of energy efficiency (23.2–28.3%) and exergy efficiency (1.8–2.5%) were obtained to vary in contrast with theoretical values of energy efficiency (24.2–28.3%) and exergy efficiency (1.9–2.8%). Overall, the system was observed to be in the good agreement with the experimental data available in the literature. Aremu and Iqbeka [139] investigated energy and exergy analyses of box type solar cookers having different insulating materials (maize cob, air, maize husk, coconut coir and polyurethane). Energy input and losses for different solar cookers with above mentioned insulating materials were reported to vary from 241.5 to 252.2 J and 224.4–234.4 J, respectively. Energy and exergy efficiencies for coconut coir were highest (37.4% and 3.9%) whereas for air, it was found lowest (11.0% and 1.0%, respectively). Overall, the importance of insulating materials in optimum designing of solar cookers was studied.

Ozturk [140] compared energetic and exergetic performance of two different solar cookers namely, solar box cooker (SBC) and solar parabolic cooker (SPC). Maximum exergy and exergy efficiencies of SBC (35.2% and 3.52%) and SPC (15.6% and 1.3%, respectively) were recorded. Moreover, the exergy efficiency was found higher than energy efficiency at high temperature conditions. Petela [141] presented the exergy analysis of a cylindrical trough-shaped solar parabolic cooker. The effect of various input parameters (geometrical configurations, heat transfer coefficients, emissivity's of surfaces, water temperatures and ambient conditions) was studied on the output parameters. The exergy efficiency of the system was reported to be relatively low (1.0%) or 10 times less than energy efficiency which was however, observed in good agreement with the experimental data available in the literature. The schematic view of cylindrical trough-shaped solar parabolic cooker is shown in Fig. 16.

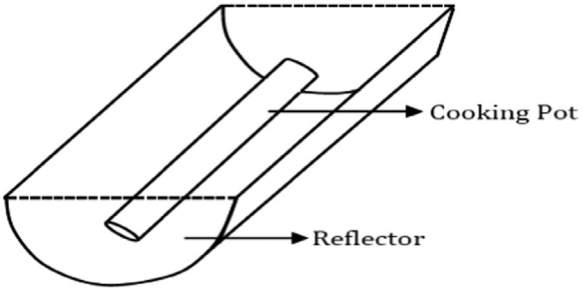

Fig. 16. Cylindrical trough-shaped solar parabolic cooker [141].

Terres et al. [142] presented energy and exergy analyses of SBC for cooking process of eggplant (Solanum melongena). The energy efficiency was observed to be 40.0% while the exergy efficiency was reported to be less than 5.0%. Thus, the difference obtained in first and second law values was used in optimum designing of the system. Kaushik and Gupta [143] investigated the energy and exergetic performance of paraboloidal solar cooker (community and domestic size). The energy, exergy and low characteristic boiling time were reported to be higher in community size as compared to the domestic size having higher optical and thermal losses. Besides, the quality of cooking meal was also observed higher in community size solar cooker.

Kumar et al. [144] presented energetic exergetic performance of a truncated pyramid solar box cooker (TPSBC) and conventional SBC for different temperature conditions (60–95 °C). For TPSBC, the quality factor (0.15), peak exergy (7.1 W) and heat loss coefficient (4.09 W/m^2K) were obtained whereas for conventional SBC, it was 0.14, 9.9 W and 4.89 W/m^2K, respectively. Moreover, exergy analysis was reported a comprehensive and realistic tool for performance evaluation of solar cookers. Mawire et al. [145] carried out energy and exergy analyses of solar cooker with oil-pebble based thermal energy storage analyzed for two different charging methods (constant flow rate and constant temperature). As compared to constant flow rate charging, high thermal energy storage was reported in constant temperature charging method. However, the energy and exergy rates were obtained high for constant flow rate charging. Moreover, high exergy rates and exergy efficiency were calculated for constant temperature charging method at high solar radiations. The schematic view of solar cooker with oil-pebble based thermal energy storage is shown in Fig. 17.

Kesarwani et al. [146] presented exergetic performance of plain and

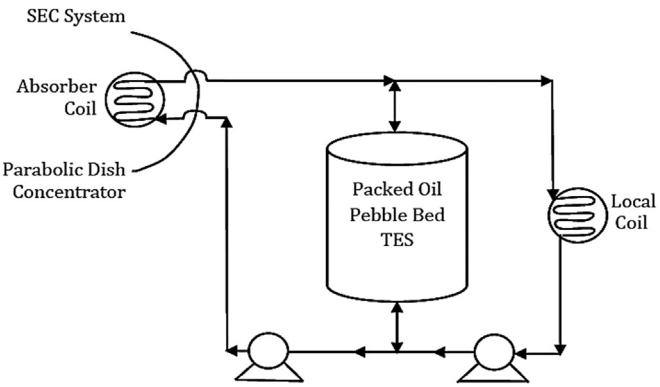

Fig. 17. Oil-pebble based thermal energy storage [145].

finned based box type solar cooker tested for the climate conditions of Allahabad, India. The exergy outputs for plain and finned based box type solar cooker were reported to be 16533.4 and 17014.4 J, respectively. However, the stagnation temperature in former was found to be 19.0% higher than latter. Prasanna and Umanand [147] presented the working performance of hybrid solar cooking integrated with LPG source. The energy accumulated from solar collector was optimized by varying flow rate through maximum power point tracking technique. The effect of pipe diameter on system efficiency was studied and proposed the method for selecting the optimum diameter of pipe to obtain maximum efficiency. Finally, the experimental and simulation results were reported good to achieve maximum power in the system. Cuce and Cuce [148] investigated energetic and exergetic performance of box type solar cookers having conventional and finned absorber plates. Rise in temperature of various solar cooker components (absorber plate, glass cover, internal air, cooking vessel and liquid) was observed through augmentation of absorber plate with fins. The maximum energy efficiency in finned absorber plate was reported to be 30.0% while the maximum exergy efficiency of the system was obtained to be 6.0% and 3.0%, respectively for summer and winter conditions. Further, the concentrating devices (like Fresnel lens or booster mirrors) were also recommended to achieve higher thermal radiations.

Terres et al. [149] presented exergy analysis of box type solar cooker having four different characteristics in terms of number of reflectors, reflector angles and reflector area. Maximum exergy efficiency of 4.2% was recorded for solar cooker having reflector angles variations of 65–85°. A significant amount of energy was also absorbed by cover glasses and contributed to loss of energy and exergy efficiency of the system. Further, the need of more process parameters was realized in optimum designing of solar cooking which was missing in the previous studies. Another study [150] also proposed the need of various process parameters (stagnation capacity, cooker weight, cost per watt, easiness handling and aesthetics) in the performance analysis of solar cookers. For this, thermal performance test, stagnation temperature, heat loss test, standard cooking time, load test, ray trace and ergonomics considerations were suggested. Shukla and Khandal [151] studied the importance of exergetic analysis of different solar collectors used in SBC and SPC. Various process (stagnation temperature, exergy output, thermal and exergetic efficiencies) were reported to increase with increase in intensity of solar radiations. Initially, the increase in exergy efficiency of SPC was observed, however, it declined later with further rise in intensity of solar radiations.

Shukla and Gupta [152] investigated energetic and exergetic performance of solar cooker integrated with linear parabolic concentrator (concentration ratio of 20) for summer and winter conditions in India. The average energy efficiency (14.0%), exergy efficiency (2.0%) and temperature of water (98 °C) were achieved in the system. The efficiency was observed low due to various heat losses such as optical losses (16%), geometrical losses (30%) and thermal losses (35%). Mohan and Vasanthakumar [153] studied the working performance of solar steam cooking having PTC with different reflectors made of aluminium and galvanized iron. The outlet temperature (140.2 °C} obtained in aluminium sheet reflector was higher than the temperature (75 °C) of galvanized iron reflector at peak solar conditions (in particular) and for different working hours (in general). Thus, the efficiency for aluminium reflector was found to be more than 30.0% whereas it was obtained below than 15.0% for galvanized iron reflector. Moreover, the nutrient quality of cooking product (such as steamed potato) was observed to be higher than boiled potato.

Gama et al. [154] evaluated the energetic and exergetic performance of SBC in the climate conditions of Algeria. The energy and exergy efficiencies obtained without reflector were found to be 13.6% and 16.2%, respectively whereas with reflector, it was found to be 0.7% and 0.9%, respectively. However, the maximum daily exergy efficiencies with and without reflector were observed to be 2.5% and 1.8%, respectively. Gavisiddesha et al. [155] investigated the thermal performance of solar cooker with paraboloid concentrator for no load and different volume of water (1 or 2 l) along with rice. The maximum cooking power (63.8 W) and exergy efficiency (7.0%) were observed initially high and decreased with time. Further, the optical efficiency and heat loss factor of the system were also determined. A similar study [156] was also carried out to investigate the working performance of SPC under no load conditions at maximum temperature of 326 °C. The heat loss factor and optical efficiency factor were evaluated using the sensible cooling curve and sensible heating curve, respectively. The overall heat loss factor was small on different days and minimal due to windshield provided at paraboloid receiver. The overall thermal efficiency of the collector was obtained to be 26.0%.

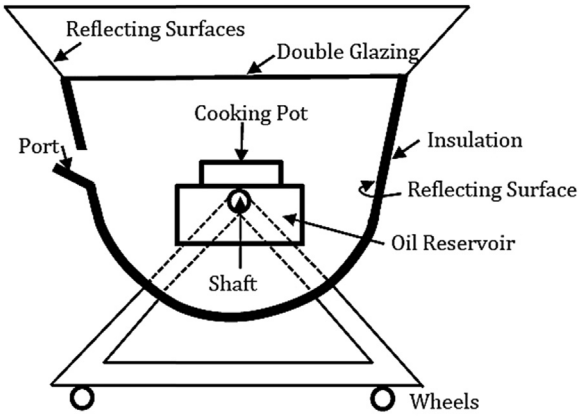

Fig. 18. Solar cooker [157].

Oturanc et al. [157] designed and developed a solar cooker for the climate conditions of Turkey. The engine oil was used as heat storing medium for preheating the cooker after cooking. The water temperature in pot was increased to normal cooking temperature in 1 h which can be further reduced by utilizing heat from oil reservoir. The average efficiency of the system was satisfactory; however, the instantaneous efficiency was observed to decrease with increase in heat loss at high temperature conditions. The schematic view of solar cooker is shown in Fig. 18.

Rikoto and Garba [158] compared the working performance of SBC for finned and unfinned cooking pots of identical shape and volume. The time required for water heating (75 cl) in finned and unfinned pots were reported to be 112 and 126 min whereas in rice cooking (0.3 kg), it was obtained to be 120 and 150 min, respectively. Therefore, the thermal performance of the system was improved by achieving better heat transfer conditions through fins. Advantages and disadvantages of different cookers are listed in Table 3.

SBC has consolidated its place particularly in domestic cooking applications and made a small but encouraging impact on the economy of developing countries. However, it has several drawbacks as listed in Table 3. The thermal performance of these systems can be enhanced through certain advancements like design augmentation in box or pot and use of reflector for higher solar gain. Whereas due to sharp focus, SPC is advantageous in terms of cooking temperature, cooking time and multiple cooking activities. But, its performance is yet to be improved as it can only perform good at higher beam radiation which is not constant and varies periodically around the year. The energy and exergy efficiencies of SPC is comparatively low and observed to vary from 2.7% to 15.6% and 1.3–10.4%, respectively for different operating conditions and food stuff. However, the overall performance of these devices can be enhanced through automatic tracking mechanisms and improving the receiver design.

7. Solar power generation

Due to exhaustible and contaminant nature of major energy

Table 3
Advantage and disadvantage of solar cooker [159].

Type of cooker	Advantage	Disadvantage
Solar box cooker	• Simple design, safe and convenient to use • Uses both direct and diffuse radiation • Requires little intervention by user • High acceptance angle and high tolerance for tracking error	• Widely divergent thermal performance • Requires regular coating of black paint • Spontaneous breakage of mirror
Concentrating solar cooker	• Can attain high temperature in small time • High thermal performance • Faster cooking	• High investment cost • Requires skilled user to operate • Strong reliance on direct beam • Low acceptance angle • Requires regular monitoring and tracking • Damage against wind, storm and hailstorm • Safety issues
Collector cooker	• Simple, safe and convenient to use • Uses both direct and diffuse radiation • Can attain high cooking temperatures • Could be used as a multicooker	• Difficult to build • Cost intensive
Panel cooker	• Comparatively good performance than box type	• Poor performance on cloudy conditions • Relies more on reflected beam

resources (like oil, gas and coal), the solar energy has found immense scope in clean power generation. Solar energy can be harnessed through PV or PV/T and concentrated solar techniques for heat and power generation applications. Solar PV is relatively a mature technology and has acclaimed major role in future electricity generation, globally. However, the performance of these devices is not stable and liable to change continuously with the intermittent nature of weather system [160]. On the other hand, the concentrated solar power (CSP) systems are under rapid development and have been widely disseminated. The CSP technology is an immerging area and has been predicted to achieve the same level of PV by 2050. These systems are also observed to be economically viable due to lower setup cost and energy storage cost. By 2050, both solar PV and CSP systems are assumed to exceed the power generation capacity of 4000 TWh/year with the occupancy of more than 10% of global electricity generation by each. The development in thermoelectric technology may also give a new thrust to the capacity of solar power generation [161]. The energetic and exergetic improvements through various integrated approaches may also be contemplated for performance enhancements of solar PV and CSP systems. The energy and exergy analyses of these systems performed by different researchers have been presented as follows:

7.1. Solar photovoltaic

Solar PV is a power system comprised of several components (solar panel, solar inverter, storage, mounting, cabling and various other electrical accessories) used to convert solar energy into the electricity. Solar energy is mainly composed of two elements namely, heat energy and light waves. When photons from the light waves allowed to fall on solar cells, the electrons get excited to higher state of energy and acts as the charge carriers to form electric current. In a study [30], the behaviour of hot carrier and light converter was examined and observed that the electrons are not only ejected in the form of heat but light also. Due to high cost of material and manufacturing, these systems are more expensive than conventional energy sources. But they are widely used in remote areas where the extension of electric grid is not an economical practice. However, the market of PV is growing rapidly in past decades because the increase in mass production is attributed to reduce the manufacturing cost at large scale [162]. Many studies have been carried out by various researchers for optimum and cost effective designing of solar PV systems.

Rahman and Chowdhury [163] presented the working performance of various PV's and studied their impact on electric utility and storage cost at peak load conditions for eastern and western parts of United States. Zahedi [164] developed the mathematical model and computational technique for PV battery to investigate its behaviour under variable load and solar radiations. Maghraby et al. [165] studied the design and working performance of PV system for three different probabilities (i.e. fixed day's battery backup and recharge, loss of load probability and Markov chain modelling). The second probability reported a reduction in number of panels and battery size. Shrestha and Goel [166] found various issues in optimum use of isolated PV for power generation in remote areas. Based on the intermittent nature of solar radiation and load requirements, different PV schemes were also presented. Moharil and Kulkarni [167] also designed a solar PV water pumping system based on the total dynamic load, azimuth angle and frictional losses.

7.1.1. Energy analysis

The energy output of a solar PV can be expressed as follows [102]:

$$Q_o = V_{oc} I_{sc} FF \tag{42}$$

Where the Fill factor (FF) is defined as

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} \tag{43}$$

The energy efficiency may be obtained as given below [168]:

$$\eta = \frac{V_{oc} I_{sc}}{I_s A_c} \tag{44}$$

7.1.2. Exergy analysis

Exergy analysis of solar PV is very important to study its thermal performance and economic feasibility. Various electrical and thermal irreversibilities may affect the performance of the system significantly at large scale. Numerous studies on exergy analysis of different PV's have been presented by various researchers and some of them are stated as: Coventry and Lovegrove [169] studied the exergetic performance of a domestic PV/T in terms of the ratio of electrical and thermal output which was obtained to be unity based on the first law analysis, however, this value was reported to increase to 17 based on the second law analysis. Thus, this change in value of dimensionless factor affected the design and cost of energy production. Another study Joshi and Tiwari [170] presented the exergetic performance of hybrid PV/T air collector in terms of exergy efficiency under optimum inclination and maximum solar gain conditions. The exergy efficiency was obtained based on the following expression as follows:

$$\varepsilon = \eta_o[1 - \beta\Delta T] + \eta_{th}\left[1 - \frac{T_0 + 273}{293 + \Delta T}\right] \quad (45)$$

Thus, the exergy efficiency of hybrid PV/T was reported to vary from 12.0% to 15.0% and 13.0–14.0%, respectively for the month of January and June in the climate conditions of Srinagar (India). Also, the total monthly amount of exergy was obtained to be 8–15 kWh. Nayak and Tiwari [171] presented exergy analysis of PV/T integrated with solar greenhouse under the combined effect of radiation exergy on south roof and PV module. The total exergy (12.8 kWh) and exergetic efficiency (4.0%) were calculated based on the following expression [135,173]:

$$\dot{E}x_{in} = A \times I_c\left[1 - \frac{4}{3}\left(\frac{T_0 + 273}{T_s}\right) + \frac{1}{3}\left(\frac{T_0 + 273}{T_s}\right)^4\right] \quad (46)$$

Similarly, the exergy input of south roof may be obtained by replacing A_c and I_c with A_{sr} and I_{sr}, respectively. Whereas the exergy output of greenhouse was calculated based on the expression given in Eq. (47) [172]:

$$\dot{E}x_{th,daily} = \sum\left(1 - \frac{T_a + 273}{T_r + 273}\right) \times \dot{Q}_{u_{daily}} \quad (47)$$

The same expression of Eq. (45) was also used to determine the exergetic performance of six PV/T flat plate water collectors connected in series for different climate conditions in India [173]. The maximum exergy was reported in summer while the annual exergy was calculated to be 1273.7 kWh. The exergy outflow was observed to be the function of thermal and electrical exergy. Raman and Tiwari [174] investigated the exergetic and economic analyses of hybrid PV/T for different cities in India. The exergy output (157.2 kWh) and exergy efficiency (14.8%) were calculated based on the expression given in Eq. (47) [175]. However, the exergy efficiency was observed 40.0% lower than thermal efficiency.

$$E_{aex} = \dot{Q}_u\left[1 - \frac{25 + 273}{T + 273}\right] \quad (48)$$

Another study [176] compared the exergetic performance of PV/T collector with or without glass cover and reported higher exergy efficiency for collector with glass cover. The results thus obtained were validated with the collected data of one day. The overall exergetic efficiency was expressed as the sum of exergy efficiency of collector and two PV cells as given in Eq. (49).

$$\varepsilon_{PV/T} = \eta_{PV} + \left[1 - \frac{T_{in}}{T_{out}}\right]\eta_{th} \quad (49)$$

Computer simulation technique has also proved to be an important tool for exergy analysis of solar devices. One such study [177] presented the exergy analysis of PV/T air collector using the following expression of exergy balance.

$$\dot{E}x_{fin} - \dot{E}x_{ini} = \dot{E}x_Q - \dot{E}x_W + \dot{E}x_{in} - \dot{E}x_{out} - \dot{I}_{cv} \quad (50)$$

The irreversibility involved in PV/T air collector was observed to be the combination of external and internal exergy losses [178]. The overall exergy efficiency of the system was obtained by using Eq. (51) as follows.

$$\varepsilon = 1 - \left(\frac{\dot{E}x_{loss} + \dot{E}x_d}{\dot{E}x_{sun}}\right) \quad (51)$$

7.1.3. Case studies

Sudhakar and Srivastava [179] presented energy and exergy analyses of 36 W solar PV for different operating parameters (module temperature, open circuit voltage, fill factor, short circuit current and overall heat loss efficiency). The energy efficiency (6.0–9.0%) and exergy efficiency (8.0–10.0%) of PV module were calculated. Moreover, the exergetic performance was observed to be the function of module temperature. Pandey et al. [180] evaluated the performance of PV module (having the hetero-junction with an intrinsic thin layer) in terms of energy, exergy and power efficiencies. Solar radiation and wind speed claimed major variations in all efficiencies (i.e. energy, exergy and power) and observed to be comparatively higher in the morning and evening than noon in the month of February in the climate conditions of north India. The average energy efficiency of the module was obtained to vary from 19.0 from 52.0% and reported to be higher than power conversion and exergy efficiencies. However, the exergy efficiency in some months (February, May, June, September, October and December) was obtained higher than power conversion efficiency whereas this trend was observed to be reversed in rest of the months. Shukla et al. [181] evaluated the performance of PV module in terms of thermal, electrical and exergy output. Different parameters (module temperature, open circuit voltage, short circuit current, overall heat loss coefficient and fill factor) were determined for the evaluation of energy efficiency (6.0–9.0%) and exergy efficiency (8.0–10.0%).

Debbarma et al. [182] experimentally studied the energy and exergy analyses of hybrid PV/T in terms of inlet and outlet temperature of air, thermal, electrical, exergetic and overall efficiencies of the system. Thus, the thermal, electrical, total, energy saving and exergetic efficiencies obtained were 44.3%, 4.9%, 56.0%, 44.4% and 9.7%, respectively. The energy per unit surface area was also observed more in hybrid PV/T as compared to PV and thermal collector alone. Ceylan and Gurel [183] performed the cooling of PV/T designed for water heating under forced circulation mode without using pump. For water temperature of 45 and 55 °C, the exergy efficiencies were obtained to be 17.0% and 21.0%, respectively. The variations due to cooling in thermal exergy of PV module, solar collector and electrical exergy of PV module were also examined. Pandey et al. [184] presented energy and exergy analyses of a multi-crystalline solar PV module in terms of energy, power conversion and exergy efficiencies in the climate zone of north India. All the efficiencies were observed higher in the month of February and as well as in morning and evening hours as compared to noon hours in general. The energy efficiency was always found higher than power conversion and exergy efficiencies. However, the higher value of fill factor resulted in higher power conversion and exergetic efficiencies.

Aoun et al. [185] experimentally studied the energy and exergy performance of a mono-crystalline PV panel in terms of energy, exergy and power energy efficiencies. On cloudy day, the energy efficiency (22.3%), exergy efficiency (12.0%) and power energy efficiency (16.0%) were obtained. However, the same were observed to be 22.1%, 15.5% and 16.8%, respectively on clear days. Naik and Palatel [186] presented energetic and exegetic performance of PV/T water heating integrated with plane reflector to enhance the concentration of solar radiations on collector. At reflector angle of 100°, an increase of 54.0% in maximum power output was reported as compared to the maximum power output obtained without reflector. Whereas an increase of 21.0% in thermal

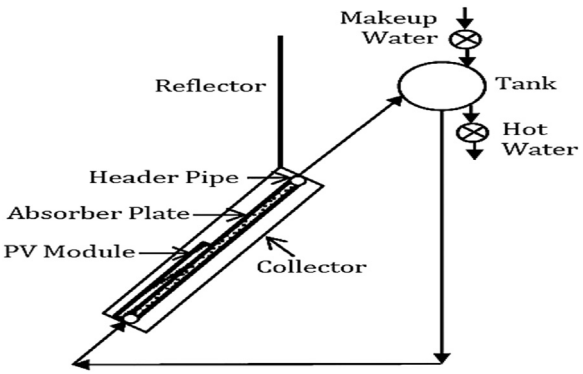

Fig. 19. PV/T water heating [186].

efficiency of collector was also found for the same tilt angle. However, an average drop of 15.0% in system efficiency was also observed with the use of reflector. The schematic view of PV/T water heating is shown in Fig. 19.

Deshmukh and Kalbande [187] evaluated the energy and exergetic performance of PV designed for DC refrigerator. For no load, the average PV efficiency (8.4%) and exergy efficiency of the system (8.2%) were calculated whereas for full load, it was obtained to be 11.4% and 11.2%, respectively. Moreover, the exergetic performance was observed to be dependent on module temperature.

Dubey and Tiwari [188] presented energy and exergetic performance of hybrid PV/T water heating for different climate conditions of various regions (Delhi, Bangalore, Mumbai, Srinagar and Jodhpur) in India. Maximum energy (4263.2 kWh) and exergy (529.7 kWh) were obtained for Bangalore while the minimum values of energy (1038.8 kWh) and exergy (196.9 kWh) were calculated for Jodhpur. Moreover, it was recommended to investigate the performance of hybrid PV/T for simultaneous production of electricity and hot water in remote and urban areas. Sidi et al. [189] evaluated the performance of monocrystalline silicon PV module in terms of exergy efficiency, electrical exergy rates and thermal exergy losses. The exergy efficiency of the system was observed to be the function of module temperature and reported a decrease of 17.5% in exergy efficiency with an increase of 10 K temperature. For 30 Wp PV module, the exergetic efficiency of 14.8–17.9% was calculated. The electrical exergy rate was obtained to increase with increase in power up to 26.7 W and then started decrease with time. Shahsavar et al. [190] investigated the energetic and exergetic performance of a naturally ventilated PV/T under glazing and unglazing. A theoretical model was also developed to validate the experimental results obtained to study the effect of various process parameters (solar radiations, channel depth, collector length and PV cell efficiency) on energy and exergetic performance of the system. Comparison of energetic and exergetic performance under glazing and unglazing is shown in Fig. 20.

Rajoria et al. [191] investigated energy and exergetic performance of PV/T (having 36 no. of PV modules) and compared the results with three configurations (case a: two parallel integrated columns each having 18 opaque PV modules in series, case b: two integrated columns connected in series each having 36 PVT tiles and case c: two parallel integrated columns having 18 semi-transparent PV modules connected in series) for different climate conditions of India. Compared to case a and case b, the case c was observed to have the low cell temperature (28.8% and 12.1%), high electrical efficiency (19.9% and 3.1%) and high air temperature (40.6% and 19.6%, respectively). Among the three cases, case c was recommended to have the highest energy saving characteristics. Kasaeian et al. [192] investigated the energy and exergetic performance of air PV/T for glazing and without glazing. In glazed air PV/T, the thermal and overall energy efficiencies were reported higher while in unglazed PV/T, the electrical and overall exergy efficiencies were obtained high. The energy and exergy efficiencies for glazed (66.0% and 11.6%) and unglazed air PV/T (52.0% and 11.0%, respectively) were recorded. Whereas the overall exergy efficiency was calculated to be 11.2–11.6% and 10.5–11.0% for glazed and unglazed air PV/T, respectively.

Fudholi et al. [193] carried out the energy and exergy analyses of PV/T water collector. For increase in mass flow rate from 0.011 to 0.041 kg/s, the primary energy saving efficiency was observed to increase from 79.0% to 91.0%. However, the entropy generation of collector was decreased with increase in mass flow rate. The total (or PV/T) efficiency was reported to vary from 58.0% to 68.0% (accounting PV efficiency of 13.0–13.8% and thermal efficiency of 45.0–55.0%). Further, the exergy efficiency of the system was reported to vary from 25.0% to 42.0% (accounting electrical exergy of 63–69 W and thermal efficiency of 57–138 W). The schematic view of PV/T water collector is shown in Fig. 21.

Izgi and Akkaya [194] presented the exergo-economic analysis of solar PV (750 Wp) system in terms of cost, energy and exergy loss rates for the climate conditions of Istanbul (Turkey). For the month of April and August, the energy and exergy efficiencies were reported to vary from 4.5% to 8.5% and 3.0–6.5%, respectively. Besides, the overall cost of energy and exergy were obtained to be 0.13–0.22 W/$ and 0.13–0.21 W/$, respectively for the same months. The exergy efficiency of different solar collector is given in Table 4.

The thermal performance of glazed PV/T are far better than solar thermal and PV alone, however, they claim less electricity efficiency and contribute to higher cost whereas the reverse is true for unglazed PV/T systems. Besides, the energy per unit surface area and improvement potential of PV/T are also high as compared to solar thermal and PV alone. The energy and exergy efficiencies of various PV/T systems are observed to vary from 45.0% to 66.0% and 17.0–21.0%, respectively while for PV, they are reported to be lower ranging from 6.0% to 9.0% and 8.0–10.0%, respectively. Various technology advancements (integration with reflector, glazing and multiple PV's column) are recommended to achieve better thermal, electrical and exergetic performance of PV/T. The cost of electricity production of these devices is high which can be reduced through optimum design and engineering.

7.2. Concentrated solar power

Development in technology advancements and market strategies for concentrating solar power (CSP) techniques such as parabolic trough,

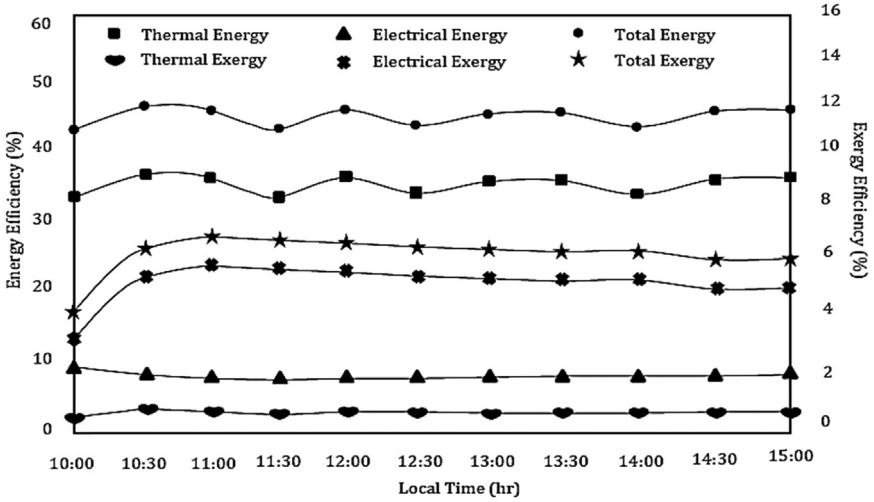

Fig. 20. Energetic and exergetic performance of PV/T under glazing and unglazing [190].

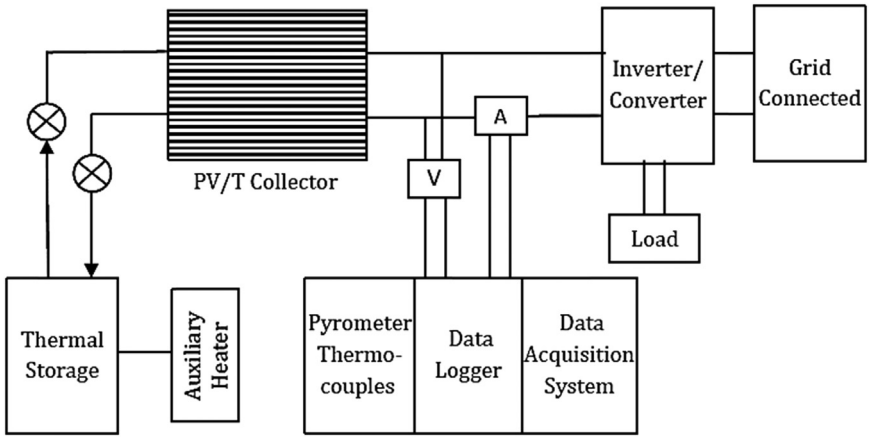

Fig. 21. PV/T water collector [193].

Table 4
Exergy efficiency of different solar collectors [195].

Solar collector	Exergy efficiency (%)
Glazed PV/T water collector	13.3
Unglazed PV/T water collector	11.0–12.9
Unglazed PV/T air collector	10.7
Glazed PV/T air collector	10.5
Unglazed PV/T air collector integrated greenhouse with earth air heat exchanger	5.5
Unglazed PV/T air collector integrated with greenhouse	4.0
Double glazed air flat plate water collector	3.9
PV array	3.0–9.0
Double glazed air collector	2.0
BIPV/T air collector	2.0

paraboloidal dish, linear Fresnel, dish/engine and power tower have been increased rapidly for the past few years. The innovative aspects of these systems are to capture and concentrate the solar energy to produce electricity at large scale. The advanced CSP systems equipped with thermal energy storage (TES) are also in recent trends for power generation in adverse climate conditions and during night working hours. The capacity factor of these systems is also high to facilitate power generation through grid integration and economic competitiveness. The CSP plant can be categorized into two groups namely, the line focusing and point focusing systems [31]. The line focusing systems (like parabolic trough and linear Fresnel) are having very high concentration factor.

Whereas the point focusing systems (like paraboloidal dish and solar power tower) require double axis tracking for efficient collection of solar energy. The technological advancements in solar concentrators and TES have attracted many stakeholders and technology players towards the direction of power generation through CSP systems. However, the major components of these systems are based on the mature technologies which require high investment cost [196]. Therefore, the energy generation efficiency of CSP systems is very low and attributed to rise of capital cost of electricity and power generation. The energy and exergy analyses provide clear assessment of various losses occurred and contribute to low performance of the entire system. Therefore, such analyses are important tool to study the techno-economic performance, future research and developments in CSP systems.

7.2.1. Energy analysis

The electric output of solar power plant may be calculated by using following expression [197]:

$$\text{Electrical output} = \frac{\text{Energy output of concentrator} \times \text{Plant efficiency}}{\text{Efficiency of concentrator}} (\text{kWh}) \quad (52)$$

Whereas the annual pumping power and energy payback period are given as follows [197]:

$$\text{Annual pumping power} = 5 \times 8 \times \text{No. of sunny days(kWh)} \quad (53)$$

$$\text{Energy payback period} = \frac{\text{Embodied energy use}}{\text{Annual electrical ouput} - \text{Annual pumping energy}} \text{ (years)} \quad (54)$$

7.2.2. Exergy analysis

The energy and exergy analyses of solar thermal aided coal-fired power plants was carried out by Suresh et al. [198] and reported the plant exergy efficiency of 33.6–38.2%. The theoretical considerations used for evaluation of exergy efficiency is given as follows:

$$\varepsilon = \frac{\text{Net electricity output}}{\text{mass flowrate of coal} \times \text{specific exergy of coal}} \quad (55)$$

Also, the exergy performance index (ExPI) is given as follows [178]:

$$\text{ExPI} = \frac{\text{Excess power generated over the design rated capacity}}{\text{Excess input through solar irradiation}} \quad (56)$$

Further, the excess input through solar irradiation may be calculated by using Eq. (57) [199]:

$$\dot{E}x_s = \left[1 - \frac{4T_a}{3T_s}(1 - 0.28\ \ln f)\right]\dot{Q}_s \quad (57)$$

7.2.3. Case studies

Baral et al. [200] investigated the energy and exergetic performance of a small scale solar assisted organic Rankine cycle (ORC) comprised of scroll expander, heat exchanger and reciprocating feed pump for electricity generation. The influence of various process parameters (evaporating and condensing pressure, the degree of superheating, pressure ratio, expander inlet and dead state temperature) on energy and exergy efficiencies of the system was studied. The overall thermal and exergy efficiencies of the system were obtained to be 7.5% and 43.7%, respectively. Knudsen et al. [201] experimentally studied the energy and exergy analyses of CSP plant working based on Kalina cycle for steam generation using two approaches (utilizing heat only from receiver and using only stored heat from thermal storage). In first approach, the use of Kalina cycle instead of Rankine cycle was reported unbeneficial since the efficiency of the former was reported 5.0% lower than the latter. However, in second approach, the efficiency of Kalina

cycle was obtained 20.0% higher than Rankine cycle. For ammonia mole fraction of 0.7, the highest efficiency of 30.7% was obtained for Kalina cycle against 30.3% for Rankine cycle.

Chaturvedi et al. [202] presented the energy and exergy analyses of solar power tower having molten salt as heat transfer medium. The influence of various process parameters (direct normal irradiations, concentration ratio and type of power cycle) on energy and exergetic performance of the system was studied. The energy efficiency of receiver was calculated to be 87.8% with small energy losses of 9.7%. However, the maximum exergy destructions of 44.2% were also reported in receiver area followed by heliostat field (33.1%). Whereas the exergy efficiencies of the whole system (24.5%) and subsystems namely, heliostat field (75.0%), central receiver (55.5%), steam generation (89.8%) and power cycle (74.5%) were obtained. Sulaiman et al. [203] studied the influence of solar energy on energy and exergetic performance of a steam power plant in Nigeria. The energy, exergy, environmental and economic analyses of different replacement models were carried out. The model accomplished with the replacement of bled off steam with high pressure heater resulted in 6.0% increase in energy and exergy efficiencies, reduction in CO_2 emission (14.0%) and payback period (0.77 years).

Wu et al. [204] developed the simulation model to carry out exergetic analysis of 5 MW solar thermal power plant. The energy and exergy efficiencies of different subsystems (high-pressure cylinder, low-pressure cylinder, condenser, deaerator and solar collecting system) were calculated. Highest exergy losses of 89.0% were reported in solar field while the highest heat losses of 72.0% were observed in condenser. Moreover, the energy and exergy efficiencies were examined to increase with increase in load conditions. The schematic view of solar thermal power plant is shown in Fig. 22.

Agrawal and Kumar [205] performed the energy and exergy analyses of a solar assisted cogeneration cycle for power generation (5.5%) and simultaneous production of refrigeration effects (7.7%) through ejector refrigeration cycle (ERC) and absorption refrigeration cycle (ARC). The irreversibility occurred in different parts (central receiver (52.5%), heliostat field (25.0%), condenser of ERC (3.9%), heat recovery vapour generator (3.8%) and ejector (3.7%)) were calculated. Whereas the energy and exergy efficiencies of the combined system were obtained to be 13.0% and 6.0%, respectively.

Tarique et al. [206] experimentally studied the energy and exergetic performance of a solar driven ORC (integrated with fuel cells and electrolyser) for hydrogen and power generation. The power generation, hydrogen generation, on-demand power generation, heat generation and cogeneration efficiencies of the combined system were obtained to be 14.9%, 7.5%, 3.7%, 31.4% and 35.0%, respectively. Moreover, the combined efficiency of power and heat production were reported to be 41.3% while the only power generation efficiency was obtained as 10.0%. Rajaei et al. [207] compared the exergetic performance of solar powered gas turbine (SPGT) and conventional gas turbine (CGT) power plant in terms of energy, exergy and environmental impacts using simulation tool. As compared to CGT with recuperator cycle, the exergy destructions and losses in SPGT were reduced to 34.9% and 47.4%, respectively. Whereas the emissions in SPGT were reported to reduce to 49.9% (CO_2), 66.1% (NO_x) and 39.7% (CO). Further, the exergy efficiencies of CGT with recuperator cycle and SPGT were obtained to be 39.4% and 26.8%, respectively. Cenusa et al. [208] investigated energy and exergetic performance of solar power plant (integrated with PTC and TES). The exergetic efficiencies of advanced and limited regenerative preheating Rankine cycle were reported to be 80.974% and 80.919%%, respectively.

Whereas the energetic and exergetic flow rates in different components (warm and hot stock, solar collectors, economizer, vaporizer and steam reheater) were observed to vary from 95.4% to 98.0% and 44.6–50.0%, respectively. Shabgard et al. [209] evaluated the exergetic performance of latent heat TES for solar power generation by imposing two major constraints (equality of TES with thermal energy recovery and solar day of 24 h). The specific phase temperature and charging time of heat transfer fluid were considered to improve the exergetic performance of TES. Corresponding to inlet temperatures of 560 and 800 °C, the optimal phase change temperatures were reported to be 475 and 715 °C, respectively. Some design modifications were also recommended to enhance the exergetic performance TES. Reddy et al. [210] presented the exergetic performance of 50 MW_e solar power plant having parabolic dish Stirling engine. The energetic and exergetic evaluation of each component (parabolic dish collector, Stirling engine, heat exchanger and cooling tower) were carried out. The major energetic losses of 42.3 kW were observed in Stirling engine followed by collector receiver (19.4 kW). While the highest exergetic losses of 32.9 kW were reported in the collector receiver followed by Stirling engine (22.1 kW). The energy and exergy efficiencies of whole system were obtained to be 77.8% and 32.0%, respectively. The schematic view of solar thermal power plant is shown in Fig. 23.

Zare and Hasanzadeh [211] presented the energy and exergy analyses of solar power plant working based on Brayton cycle (using helium as working fluid) and integrated with two ORC's for waste heat recovery of Brayton cycle. The effect of various process parameters (direct normal irradiation, concentration ratio, heliostat field efficiency, compressor pressure ratio, gas turbine inlet and evaporator temperatures) on energetic and exergetic performance of the system was studied. The higher exergy efficiency of 70.0% was reported alone for solar power tower whereas for overall power plant, it was obtained to be around 30.0%. Liu et al. [212] investigated the thermodynamics performance of solar power system (using oil and molten salt as heat transfer fluids) for feed water heating and steam superheating, respectively. As compared to solar power system, the exergy losses in proposed process were reduced by 7.8% (for oil) and 45.2% (for molten salt). Besides, the average solar to electric efficiency and nominal efficiency were obtained to be higher as 15.8% and 22.8%, respectively. Moreover, the thermo-economic performance of the proposed system was improved.

Mukhopadhyay and Ghosh [213] presented energy and exergy analyses of solar power tower plant with TES. The waste heat of Brayton cycle was utilized for driving steam turbine through heat recovery steam generator. The maximum power of 2.4 MW was obtained from the combined system with an overall efficiency of 27.0%. At pressure ratio of 4.0, highest exergy destructions were found in solar receiver (> 40.0%) followed by heliostat (~10.0%) and process heater (~3.0%). However, the exergy destructions of solar receiver were observed to decrease with increase in pressure ratio. Martin et al. [214] evaluated the thermo-economic performance of solar combined cycle categorized in three modes (parabolic troughs with oil at intermediate cycle pressure (SF1), low cycle pressure (SF2) and Fresnel collectors at low cycle pressure (SF3)). The energy and exergy efficiencies of SF1 (70.0% and 46.9%), SF2 (74.0% and 44.3%) and SF3 (71.0% and 37.0%, respectively) were evaluated under solar mode. Whereas the overall energy efficiency (54.4%) and exergy efficiency (52.4%) of the

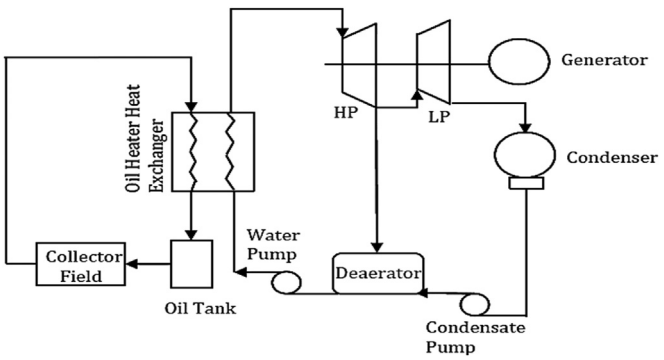

Fig. 22. Solar thermal power plant [204].

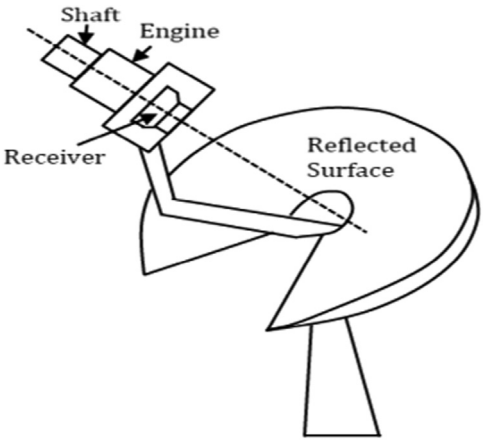

Fig. 23. Solar thermal power plant [210].

system were reported to be higher in fuel mode for all the three modes. As compared to the combined cycle, the investment cost, running cost and emissions were small in cycle with solar mode only.

Cau and Coccu [215] compared the performance of solar power plant working based on ORC (integrated with parabolic trough and linear Fresnel). The highest specific energy produced by linear Fresnel was reported to vary from 55 to 60 kWh/m^{2}y against the parabolic trough having specific energy production of 45–50 kWh/m^{2}y. However, the cost of energy production through linear Fresnel (380 €/MWh) was estimated to be more than parabolic trough (340 €/MWh) [216]. Reddy et al. [217] presented the energy and exergy analyses of Linear Fresnel Reflector Solar Concentrator aided natural gas fired cycle power plant. As compared to the energetic analysis, the effect of solar contribution in feed water heating and low pressure steam generation was more significant in exergetic analysis. The energy and exergy efficiencies of the system were observed to increase with increase in normal beam radiation. While increasing the mass flow rate of thermic fluid, the energy and exergy efficiencies were found to be increased and decreased, respectively. Status of various CSP technologies has been given in Table 5.

CSP systems are quite complex and involve various time consuming processes related to their design, development, installation and commissioning. Due to unavailability of basic requirements (such as infrastructure, skilled manpower and government support), the power generation capacity is low and expensive, particularly at small scale. The working performance of each CSP technique highly depends on the climate conditions especially the direct normal radiation, therefore, the site selection plays an important role to achieve the required targets in terms of power generation capacity and future investments. The energy and exergy efficiency of different solar power systems (solar power tower, solar thermal power plant, solar gas power turbine, dish/engine, Kalina, Rankine and Brayton cycle) are observed to vary from 13.0% to 77.8% and 6.0–43.7%, respectively. The highest exergy destructions are caused by heliostat field, receiver and evaporator. Also, the waste heat from different power cycles can be utilized in combination with high grade energy for performance enhancements.

8. Discussion of results

So far, the energy and exergy analyses of different solar energy systems under different climate and operating conditions have been discussed with their advantages and disadvantages. In general, the energy efficiency of solar energy systems is much higher than exergy efficiency because the exergy represents the energy quality and thus it always enhances with increase in temperature conditions unlike the quantity of energy. However, each solar energy system has their own importance and significance depending upon the end use application, operating condition and techno-economic feasibility. From the various studies on solar drying [64–74], the active indirect solar dryers are more practical for quality drying of various commodities. However, the solar collector used is attributed to higher exergetic losses and thus reduces the overall drying performance of the system. The higher exergetic losses in collector unit are due to the presence of various energy losses (conductive, convective and radiative) in different directions. These losses can be minimized through selective surfaces, multi glass covers with high transmissivity, optimum insulation and design augmentation of collector unit. Unlike energy, the exergy, once lost cannot be recovered and it is found more in collector receiver assembly beside the low temperature utility unlike energy. The thermal energy storage in solar drying plays an important role in energy conservation and maximizing the use of available energy.

Therefore, the energetic and exergetic performance of solar drying

Table 5
Status of various CSP technologies [218].

Components	Parabolic trough	Solar tower	Linear Fresnel	Dish-Stirling
Maturity of technology	Commercially proven	Pilot plants, commercial projects	Pilot projects	Demonstrated projects
Technology risk	Low	Medium	Medium	Medium
Operating temperature of solar field (°C)	290–550	250–650	250–390	550–750
Plant peak efficiency (%)	14.0–20.0	23.0–35.0	18.0	30.0
Annual solar to electricity efficiency (%)	11.0–16.0	7.0–20.0	13.0	12.0–25.0
Annual capacity factor (%)	25–28 (no TES) 29–43 (7 h TES) 70.0–80.0 Suns	55.0 (10 h TES)	22.0–24.0	25.0–28.0
Collector concentration	70–80 Suns	> 10000 Suns	> 60 Suns	> 1300 Suns
Cycle	Superheated steam Rankine	Superheated steam Rankine	Saturated stream Rankine	Stirling
Receiver/absorber	Absorber attached to collector, moves with collector	External surface or cavity receiver, fixed	Fixed absorber, no evacuation, secondary reflector	Absorber attached to collector, moves with collector
Storage system	Indirect 2-tank molten salt at 380 °C or Direct 2-tank molten salt at 550 °C	Direct 2-tank molten salt at 550 °C	Short term pressurized steam storage (< 10 min)	No storage, chemical storage under development
Storage with molten salt	Commercially available	Commercially available	Possible, but not proven	Possible, but not proven
Grid stability	Medium to high	High	Medium	Low
Steam conditions (°C/bar)	380 to 540/100	540/100 to 160	260/50	–
Water requirement (m^3/MWh)	3 (wet cooling) 0.3 (dry cooling)	2–3 (wet cooling) 0.25 (dry cooling)	3 (wet cooling) 0.2 (dry cooling)	0.05–0.1 (mirror washing)
Suitability for air cooling	Low to good	Good	Low	Best

Table 6
Summary of energetic and exergetic performance of various solar energy applications.

Investigator	Type of solar system	Energetic performance	Exergetic performance	
			Exergy efficiency	Exergy losses
Solar drying				
Bolaji [64]	Direct, indirect and mixed mode	77.0%[a]	33.4–55.2%	–
Akinola and Fapetu [66]	Mixed mode dryer	66.9%[b]	56.0%	44.0%
Chowdhury et al. [67]	Solar tunnel dryer	42.5%[a]	41.4%	–
Fudholi et al. [68]	Indirect solar dryer	35.0%[b]	30.0%	–
Hadi et al. [71]	Forced convection solar dryer	–	80.0%	32.0 W
Panwar [72]	Thin layer solar drying	37.9%[a]	79.4%	–
Doblada et al. [74]	Microalgae solar dryer	1.5%[a]	28.0%	–
Solar refrigeration and air conditioning				
Baiju and Muraleedharan [86]	Solar hybrid adsorption refrigeration	0.45[c]	11.0–79.8%	1.2 kW
Khaliq et al. [87]	Solar driven triple staged refrigeration	10.0%[a]	4.0%	52.5%
Jain et al. [89]	Solar driven ejector refrigeration	5.8%[b]	0.2%	3.1 kW
Kanoglu et al. [92]	Open cycle desiccant cooling	0.35[c]	11.1%	0.4 kW
Gunhan et al. [99]	Solar assisted licl-H_2O absorption cooling	–	13.1–43.2%	4.9–66.1%
Siddiqui et al. [100]	Solar driven absorption refrigeration	FPC (20–75.0%)[a]	29.56%	0.4 kW
Solar water heating				
Pandey et al. [109]	ETC solar water heater	66.6%[a]	13.4%	–
Liu et al. [111]	Solar water heating system	Solar collector (50.3%)[a], Heat exchanger (99.8%)[a], Thermal storage (4.4%)[a], Water storage (98.6%)[a]	Collector (1.7%), Heat exchanger (78.0%), Thermal storage (4.0%), Water storage (93.0%)	99.3%
Gang et al. [116]	CPC solar water heater	49.0%[b]	4.6%	–
Tiwari et al. [118]	Solar PV/T water heater	48.8–54.0%[b]	9.0–14.5%)	–
Daghigh and Shafieian [123]	ETC solar water heater	± 1.2%[b]	± 5.1%	99.0%
Mahfuz et al. [124]	TES solar water heater	63.8 – 77.4%[a]	6.0– 9.5%	TES (6.9 kWh)
Daghigh and Shafieian [125]	ETC solar water heater	± 1.2%[b]	± 4.6%	–
Solar cooking				
Panwar [126]	Animal feed solar cooker	23.2–28.2%[a]	1.8– 2.4%	641.3 kJ/day
Aremu and Iqbeka [139]	SBC	37.3%[a]	3.9%	234.4 J
Mawire et al. [145]	TES solar cooker	~70.0%[a]	~27.5%	–
Terres et al. [149]	SBC	20.0%[a]	4.2%	SBC 1 (~580 kJ)
Shukla and Gupta [152]	Linear parabolic solar cooker	14.0%[a]	2.0%	–
Gama et al. [154]	Box type solar cooker	Reflector (0.73%)[a] and without reflector (13.6%)[a].	With reflector (0.9%) and without reflector (16.2%).	–
Solar PV				
Sudhakar and Srivastava [179]	Solar PV	6.0–9.0%[a]	8.0–10.0%	~0.29 W
Pandey et al. [184]	Multi-crystalline solar PV module	18.8%[a]	12.7%	–
Naik and Palatel [186]	PV/T solar water heating	without reflector (74%)[a]	Without reflector (~5.2%)	–
Sidi et al. [189]	Mono-crystalline silicon PV module	–	18.0%	3.4 W
Shahsavar et al. [190]	Naturally ventilated PV/T	For glazed and unglazed, (22.5–44.9%)[a], (12.2–36.2%)[b]	For glazed and unglazed, total exergy efficiency (6.0–9.0%), thermal exergy efficiency (0.3–1.1%), electrical exergy efficiency (3.9–8.7%)	–
Fudholi et al. [193]	Solar PV/T water collector	55.0%[b]	42.0%	–
Izgi and Akkaya [194]	Solar PV	8.5%[a]	6.5%	~3.8 kW
Concentrated solar power				
Baral et al. [200]	Solar assisted ORC	7.2%, 7.54%[b]	43.7%	1.12 kW
Chaturvedi et al. [202]	Solar power tower	Receiver (87.7%)[a]	24.5%	5647.9 kW
Wu et al. [204]	Solar thermal power plant	HP cylinder (90.3%)[a], LP cylinder (79.1%)[a], condenser (6.7%)[a], deaerator (99.9%)[a], solar collector (78.7%)[a]	HP cylinder (71.4%), LP cylinder (16.0%), condenser (1.5%), deaerator (53.7%), solar collector (31.4%)	Condenser (72.0%)
Agrawal and Kumar [205]	Solar assisted cogeneration cycle	13.0%[a]	6.0%	Receiver (52.5%)
Cenusa et al. [208]	Solar power plant integrated with PTC	95.4–98.0%[a]	44.6–50.0%	–
Reddy et al. [210]	Parabolic dish Stirling engine	67.1–78.2%[a]	51.2–59.7%	55.0 kW

(continued on next page)

Table 6 *(continued)*

Investigator	Type of solar system	Energetic performance	Exergetic performance	
			Exergy efficiency	Exergy losses
Zare and Hasanzadeh [211]	Brayton cycle solar power plant	23.1%[a]	23.2%	49106 kW
Mukhopadhyay and Ghosh [213]	Solar power tower plant with thermal storage	~31.0%[a]	~37.0%	Receiver (~42.0%)
Martin et al. [214]	Solar combined power cycle	54.4%[a]	52.4%	–

[a] Energy efficiency.
[b] Thermal efficiency.
[c] Coefficient of Performance.

unit can be improved and maintained through thermal storage provided a thorough study of PCM's in terms of chemical stability, storage capacity and economic viability. On the other hand, the solar refrigeration and air conditioning are energy intensive processes and thus bears a huge cost to achieve the required cooling and thermal comfort at different scale in domestic and industrial sectors. Overall energy losses in these systems are significantly higher due to the involvement of various moving components in the process cycle. Therefore, the quantitative information related to energy utilization and conservation are required to design an efficient and eco-friendly system. The COP value of these systems are reported to be highest for 50% system charging (refrigeration effect is highest and compressor work is small). Whereas the exergetic performance of solar refrigeration and air conditioning is poor which indicates the involvement of high irreversibilities in the system. In a study [219], the highest exergy efficiency (45.9%) is calculated at the evaporator temperature of 7 °C when the system is 100% charged. While it is found least (3.5%) for the evaporator temperature of 24.5 °C and 25% system charging. The reduced exergy efficiency has been observed as the refrigerant temperature tends to approach the reference temperature and thus attributed to small exergy content. Among different refrigerants, the LiBr-H_2O combination are generally used in solar air conditioning systems, however, it crystallizes during operation and increase the absorber temperature. The highest exergetic losses have been found in compressor which becomes even more for using reciprocating compressor due to friction between cylinder and piston rings. However, these losses can be reduced through lubrication but still more prominent in reciprocating compressor.

The ETC based water heater are very popular in modern scenario of solar water heaters. The working performance of solar water heater are highly dependent on the solar radiations and water flow rates. With increase in solar radiation, both the energetic and exergetic efficiencies increases with time and keeps increasing to attain peak values even with decrease in solar radiation. However, the energetic and exergetic efficiencies decreases afterward with decrease in solar radiation. Whereas the energetic and exegetic performance of ETC based solar water heater has been observed to improve with increase in flow rate up to optimum values only. One such study [109] reported maximum energetic efficiency (66.6%) and exegetic efficiency (13.4%) of ETC based solar water heater for the optimum water flow rate of 15 l per hour. SBC is very common for cooking practices especially in the developing counties, however, it has some bottlenecks in their operation as listed in Table 3. Whereas due to sharp focus, SPC has gained more popularity in the recent trend of solar cooking. It is advantageous in terms of cooking temperature, cooking time and multiple cooking activities. The output exergy of solar cooker has been observed to be dependent on the volume/weight of cooking commodity. In general, the average exergy efficiency of SPC is higher than SBC for the same operating conditions [137]. However, in some studies, the energy efficiency is found to be higher than exergy efficiency because the former is based on the first law of thermodynamics which deals only with the quantity of energy while the latter is based on the second law of thermodynamics which deals with the quality of energy and includes irreversibilities/losses due to various dissipative effects (Friction, flow field, magnetic hysteresis, resistances etc.).

The overall performance of SPC can be enhanced through automatic tracking mechanisms and improving the receiver/pot design. The energy, power conversion and exergy efficiencies of thin film PV varies with solar radiations. For thin film and multi-crystalline based PV, the exergy efficiency is observed to be more than energy and power conversion efficiencies because exergy efficiency highly depends on wind speed, solar radiations, ambient and module temperatures. All the three efficiencies attain their peak values and then decreases sharply. This fact can be explained with increasing and decreasing trend of solar radiations from morning to noon and noon to evening, respectively throughout the day. Also, the module temperature in the morning is low and attributed to high voltage whereas with increase in time, the module temperature increases and results in low voltage of module. CSP systems are an emerging technology for solar power generation. Except parabolic trough, rest of the technologies (solar tower, linear Fresnel and dish Stirling) are either at pilot scale or yet to be developed. The power generation capacity of CSP systems is low and cost intensive. The collector-receiver assembly is found to have the highest exergetic power losses and thus it has high improvement potential for performance enhancements of the power cycle. The energetic and exergetic analysis of different components of solar power plant gives a more representative performance evaluation of possible configurations of the existing system.

Moreover, more studies are required to investigate the exergetic behaviour of different components of solar energy system under different climate and operating conditions. Optimization and simulation studies can be helpful to examine the realistic performance of these systems beforehand.

9. Conclusion

In the present study, a comprehensive review on energy and exergy analyses of various typical solar energy technologies (solar drying, solar refrigeration and air conditioning, solar water heating, solar cooking and solar power generation through solar PV and concentrated solar power) used for various heat and power generation applications have been carried out. The first law of thermodynamics deals only with the quantity of energy and asserts energy change of system without considering quality of energy which is more important to identify the work potential and realistic behaviour of existing system. Therefore, the energy and exergy analyses are very useful to investigate the performance characteristics and economic viabilities for sustainable development of the technology. In addition, such analyses are also helpful in exploring new opportunities for developing energy and exergy management strategies of the nation. The present article has extracted and summarized the following concluding remarks as follows:

- In general, the energy efficiency has been found to be more than that of exergy efficiency. However, the reverse is true in some studies because the former is based on the first law of thermodynamics which only deals with the quantity of energy while the latter is based on the second law of thermodynamics which consider the quality of energy and irreversibilities due to various parameters.
- In most of the studies, the influence of various process parameters (mass flow rate, solar radiation, inlet temperature and time) on exergetic performance of the system has been analyzed and found that the energy and exergy efficiencies are highly dependent on the intensity of solar radiations on daily basis.
- Energetic and exergetic performance of various solar energy systems with TES unit have been improved, however, TES units are required to be investigated thoroughly in terms of physical and chemical properties of heat transfer fluids.
- Solar collector in most studies has claimed the highest exergy destructions therefore, highest exergetic improvement potential can be achieved through design augmentation of collector unit. Similarly, is the case with collector receiver in concentrated solar power systems.
- The performance evaluation of solar drying on product/fuel basis along with various process parameters (inflow, outflow and loss of exergy) can result in complete energy and exergy analyses of drying unit for various commodities.
- Overall exergetic performance of solar refrigeration and air conditioning system is more when the system is fully charged, however, it will lead to higher compressor work and decrease COP of the system.
- As compared to SBC, the performance of SPC has always been reported better in terms of temperature, cooking time and efficiency. However, the automatic tracking of parabolic dish will lead to minimize the overall energy losses.
- All the efficiencies of modules covered under this study have been examined to more in the morning and evening hours as compared to noon hours. Whereas the efficiencies in the morning hours are also found more than the evening hours due to variations in ambient and module temperature throughout the day.
- The exergetic efficiency of PV/T has been observed to increase with increase in mass flow rate and found better than PV and solar thermal collector alone in different aspects of performance and economic benefits.

In comprehensive review, most of the studies have reported exergy destructions of various system components with different magnitude and location. However, the preventive measures and information related to the reduction or elimination of exergy losses for performance enhancements of the system are scanty. More investigations are required to study the chemical stability and compatibility of heat transfer fluid with TES to achieve better heat transfer conditions. Also, more emphasis are required to be made on the system components claiming high exergy destructions through optimum engineering and simulation techniques. The cost of electricity generation in PV/T is high and can be reduced by inventing the advanced but cheap materials. In solar drying, the drying characteristics of various commodities may be improved through pre-treatment techniques contribute to reduce both drying time and energy requirements. The line or point focus can be improved through automatic tracking mechanisms and simulation tools. Also, the techno-economic and cost analysis of different components of the system will be helpful to study the technological feasibility and economic viability of the whole system. Moreover, the performance evaluations of solar energy systems require advancements in terms of computing techniques and research methodologies. Therefore, an opportunity can be taken up to explore this vital area for future research.

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